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INVESTIGATIONS RELATING TO THE EXTENSION OF LAMINAR FLOW BY MEANS OF BOUNDARY-LAYER SUCTION THROUGH SLOTS

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SUMMARY

Experimental investigations have been made of boundary-layer suction through slots as a means of increasing the extent of laminar flow on airfoil sections. The tests were directed, first, toward the determination of suitable types of suction slots and, second, toward the determination of the effectiveness of boundary-layer control as a means of increasing the extent of laminar flow in regions of favorable and unfavorable pressure gradient. The Reynolds number range of the tests extended up to 10.0×10^6. The investigations were made in 1939 and 1940.

The results show that, with the use of suitable slots, substantial increases in the extent of laminar flow can be achieved by boundary-layer control with only a small expenditure of power up to free-stream Reynolds numbers as high as about 7.0×10^6. Appreciable increases in the extent of laminar flow could not be obtained at higher values of the Reynolds number. The difficulties apparently arose as a result of the introduction of disturbances into the boundary layer. The origin and nature of these disturbances must be investigated further before any final practical evaluation of boundary-layer control through slots as a means of increasing the extent of laminar flow can be made.

With the aid of the experimental data, a suction-slot power-loss analysis has been made which permits a rational approach to the design of an optimum suction-slot arrangement requiring a minimum expenditure of power for an arbitrary airfoil operating under any given set of conditions.

INTRODUCTION

Much interest has been shown recently in the possibility of increasing the extent of laminar flow obtainable in regions of both

favorable and unfavorable pressure gradient by removing a portion of the boundary layer through slots. In the absence of extraneous effects such as might result from surface imperfections and free-stream turbulence, the extent of laminar flow is believed to be limited either by transition that results when excessively high values of the boundary-layer Reynolds numbers are reached or by transition that results from laminar separation. In a region of favorable pressure gradient, the purpose of the boundary-layer removal is merely to limit the growth of the boundary layer in such a way that the boundary-layer Reynolds number for transition is not exceeded. In a region of unfavorable pressure gradient, however, laminar separation as well as excessive values of the boundary-layer Reynolds number may limit the extent of laminar flow so that the purpose of the boundary-layer removal in this case is twofold.

Several experimental investigations concerned with the extension of laminar flow by means of suction slots have been carried out by Holstein in Germany (references 1 and 2) and by Pfenninger in Switzerland (reference 3). These investigations were made at values of the airfoil-chord Reynolds number between 0.5×10^6 and 4.0×10^6 and were directed toward extending the laminar layer into a region of unfavorable pressure gradient in such a manner that the sum of the wake and suction-power drags would be less than the drag of the plain airfoil. Significant net drag savings resulting from the boundary-layer removal were observed by both Holstein and Pfenninger at low values of the Reynolds number. For example, Pfenninger's best results which showed a net drag saving of 50 percent were obtained at a Reynolds number of 2.0×10^6. Neither of these investigators was able, however, to obtain any net drag savings at Reynolds numbers as high as 4.0×10^6.

The difficulties which prevented the attainment of net drag savings at the higher Reynolds numbers were not clearly determined in the investigations described in references 1 to 3. Furthermore, except for some rather limited data obtained in flight (reference 4), no results are available which are pertinent to the problem of increasing the extent of laminar flow in a region of favorable pressure gradient.

Some information on these and other problems may be obtained from the results of experimental investigations made at the Langley Laboratory in 1939 and 1940. These investigations were initiated to explore the possibility of using suction slots to increase the rather low value of the Reynolds number at which the transition position moved forward on the NACA low-drag airfoils of early design. The results of these investigations, which were conducted at Reynolds

numbers up to about 10.0×10^6, have recently been analyzed and are given in the present paper. These results were not presented at the time of the tests because the transition difficulties with the early tests of the low-drag airfoils were eliminated by screening out nearly all of the residual free-stream turbulence of the wind tunnel. As a consequence, it was thought at the time that the importance of research on boundary-layer removal was considerably lessened and that time and effort could be spent more profitably on the further investigation of the low-drag type of airfoil.

The test results presented and discussed are divided into three parts: The first pertains to the design of slots; the second, to the extension of the laminar layer in a region of unfavorable pressure gradient; and the third, to the extension of the laminar layer in a region of favorable pressure gradient. Four different airfoils were employed in these investigations, not in any attempt to study specific airfoils but rather to obtain pressure distributions of a desired type. In addition to a discussion of the results as they pertain to the effectiveness of suction slots as a means of increasing the extent of laminar flow under various conditions, the three groups of test results were also analyzed for the purpose of determining the general conditions necessary for limiting the growth of the boundary layer with a minimum expenditure of suction power.

SYMBOLS

x	distance along airfoil chord
x'	length of flat-plate flow required to develop a given-size boundary layer at a local velocity U
y	distance perpendicular to airfoil surface
c	airfoil chord
l	distance along surface behind a slot
w	slot width
U	local velocity outside boundary layer
u	local velocity inside boundary layer
U_o	free-stream velocity

p	local static pressure
p_o	free-stream static pressure
H	total pressure
H_o	free-stream total pressure
ρ	mass density
q	local dynamic pressure $\left(\frac{1}{2}\rho U^2\right)$
q_o	free-stream dynamic pressure $\left(\frac{1}{2}\rho U_o{}^2\right)$
S	pressure coefficient $\left(\frac{H_o - p}{q_o}\right)$
ΔQ	suction flow quantity per unit span through single slot
Q_{bl}	flow quantity per unit span in boundary layer out to $\frac{u}{U} = 0.997$ at a station just forward of slot
$\Delta Q/Q_{bl}$	fraction of flow removed from boundary layer at a particular slot
ΔC_Q	single-slot flow coefficient $\left(\Delta Q/U_o c \quad \text{or} \quad 1.64 \frac{\Delta Q}{Q} \frac{R_\delta}{R}\right)$
C_Q	total flow coefficient for all slots in use $\left(\Sigma\ \Delta C_Q\right)$
C_P	suction-pressure-loss coefficient $(\Delta H/q_o)$
Δc_{d_s}	drag-coefficient equivalent of single-slot suction power $\left(C_P\ \Delta C_Q\right)$
c_{d_s}	drag-coefficient equivalent of suction power for all slots in use $(\Sigma\ \Delta C_Q C_P)$

δ	boundary-layer thickness defined as distance perpendicular to surface at which $\frac{u}{U} = 0.707$
$\delta_{0.997}$	boundary-layer thickness defined as distance perpendicular to surface at which $\frac{u}{U} = 0.997$
δ^*	boundary-layer displacement thickness $\left(\int_0^\infty \left(1 - \frac{u}{U}\right) dy\right)$
θ	boundary-layer momentum thickness $\left(\int_0^\infty \left(1 - \frac{u}{U}\right) \frac{u}{U}\, dy\right)$
μ	viscosity
ν	kinematic viscosity (μ/ρ)
R_1	Reynolds number per unit length based on local velocity outside boundary layer $(\rho U/\mu)$
$R_{x'}$	Reynolds number based on local velocity outside boundary layer and distance x' $(\rho x' U/\mu)$
R	Reynolds number based on wing chord and, unless otherwise specified, free-stream velocity $(\rho U_o c/\mu)$
R_δ	boundary-layer Reynolds number $(\rho U \delta/\mu)$
R_θ	boundary-layer Reynolds number $(\rho U \theta/\mu)$
K_d	slot total-pressure-loss coefficient based on test data
K_h	slot total-pressure-loss coefficient based on assumed hyperbolic function
K	slot-pressure-loss correlation coefficient $\left(K_d/K_h\right)$

Subscripts:

1, 2, 3, 4, 5 refer to stations employed in slot analysis (see fig. 11)

A bar is used over symbols to indicate an integrated mean value.

WIND TUNNEL AND MEASURING APPARATUS

All the tests were made in the Langley two-dimensional low-turbulence tunnel. The test section of this tunnel is 7.5 feet high, 3.0 feet wide, and 7.5 feet long, and the models, when mounted, completely spanned the 3-foot dimension. The variation of the free-stream turbulence level of the tunnel with speed, both before and after the turbulence-reducing screens were installed, is shown in figure 1. The tests described in the present paper were made before the installation of the turbulence-reducing screens. All boundary-layer measurements were made by means of a rake of total-pressure tubes of the type described in reference 5, and pressure-distribution measurements were made with a static tube located near the surface of the airfoil. All suction quantities were determined by means of an orifice plate of approximately 1-inch diameter. The Reynolds number was varied by varying the tunnel airspeed. A more complete description of the tunnel and test methods is included in reference 6.

DESCRIPTION OF INVESTIGATIONS

The various investigations are described in some detail in this section of the paper. The results obtained from these investigations are considered in a subsequent section entitled "Results and Discussion."

Slot Geometry and Arrangement

Types of slot.- The determination of a desirable type of suction slot is a twofold problem. An efficient slot which operates with small pressure loss is, of course, desirable; but, of even greater importance, the slot should not in itself so disturb the external flow as to cause transition. The investigations to determine a suitable slot were made with a 5-foot-chord wooden model of the NACA 18-212 airfoil section. A sketch of the airfoil profile and its measured and theoretical pressure distribution are shown in figure 2. The different types of slots were installed near the midchord position, at which point the boundary-layer thickness δ was varied from approximately 0.035 inch to 0.025 inch by varying the tunnel airspeed.

The corresponding range of airfoil-chord Reynolds number extended from approximately 4.7×10^6 to 8.0×10^6. Internal total-pressure-loss measurements in the suction air were made for a variety of types of suction slots for a range of tunnel speeds and suction quantities. Boundary-layer surveys were also made at different distances behind each slot for different combinations of tunnel speed and suction quantity to determine the conditions under which the slots themselves became critical and tended to cause transition. In general, the range of pertinent test conditions investigated was chosen to include those conditions encountered in the investigations of the effectiveness of suction slots in favorable and unfavorable pressure gradients.

Slots of various types and sizes were investigated. The greater number of these slots were of the type which are cut normal to the surface of the wing and will hereinafter be referred to as normal slots. The variations in size and contour of the normal slots investigated are shown in figure 3. The slot widths varied from 1/16 inch to 1/64 inch which correspond to a range of approximately 0.40 to 2.25 for the ratio of boundary-layer thickness δ to slot width w. Slots were tested with sharp slot-entry lips, with both lips rounded, and with one lip rounded. The radii of the rounded lips were varied from one-fourth to twice the slot width. Several configurations having the rear wall of the slot displaced upward (types B_1 and B_2 of fig. 3) were tested in an effort to reduce the disturbance caused by removal of a portion of the boundary-layer air. No effort was made to determine the effect of diffuser shape within the slot.

A few tests were made of backward opening slots having widths of 1/64 inch to 1/16 inch (fig. 4). Also investigated were configurations consisting of rows of holes and of a slot covered with screen. The arrangement employing the holes is shown in figure 4 and is seen to consist of holes placed in rows 1/8 inch apart. The tests of this configuration were made for sizes of hole varying in diameter from 0.025 inch to 0.045 inch. The screen arrangement consisted of a 60-mesh screen placed over a $\frac{1}{4}$-inch normal slot as shown in figure 4.

For all of these preliminary investigations, the slots were formed by cutting directly into the wooden surface of the model.

Slot spacing.- In connection with the problem of restricting the growth of the boundary layer to avoid transition, the question arises as to whether the power required for suction depends on the number of slots, that is, whether the desired thinning of the boundary layer can be accomplished through one large slot as

efficiently as through a number of smaller slots distributed along the length of flow.

In order to investigate this problem, measurements were made of the suction power necessary to limit values of the boundary-layer Reynolds number at various distances downstream of the slot to the value of the boundary-layer Reynolds number occurring immediately upstream of the slot. A 90-inch-chord wooden model of the NACA 27-215 airfoil section was employed for these tests. Data showing the test configuration are given in figure 5. A single slot of $\frac{1}{32}$-inch width was located at 30 percent chord. The airfoil pressure gradient was therefore favorable for a rather large distance behind the slot. The tests were made at speeds corresponding to three values of the boundary-layer Reynolds number R_{δ} of 2940, 3400, and 3870 immediately upstream of the slot. The wing Reynolds numbers were 5.7×10^6, 8.1×10^6, and 9.9×10^6, respectively. By variation of the amount of suction, these values of R_{δ} were maintained at 10 positions downstream of the slot. The farthest position behind the slot was 24 inches (fig. 5).

An effort was also made to determine the proportion of the total flow in the boundary layer that must be removed at a slot in order to effect a given decrease in boundary-layer Reynolds number across the slot. For this purpose, boundary-layer measurements were made 1/2 inch in front and behind a slot for various amounts of suction and different Reynolds numbers. The boundary-layer Reynolds number in front of the slot without suction varied from 2200 to 3600.

Suction Slots in an Unfavorable Pressure Gradient

An airfoil section having a moderately unfavorable pressure gradient over a large portion of the chord was desired for the investigations of the effectiveness of suction slots as a means of extending laminar flow in regions of unfavorable pressure gradient. The NACA 0007-34 airfoil section was employed in these investigations because of its rather long extent of moderate unfavorable pressure gradient. The chord of the wooden test model was 10 feet. The surfaces of the model were painted and sanded until an aerodynamically smooth finish was obtained.

Because of the large chord of the model, the orifices in the tunnel wall normally used to determine the tunnel speed were very close to the leading edge of the model; therefore, the tunnel

calibration factor was changed by an unknown amount. The shape of the measured airfoil pressure distribution can be seen, however, in figure 6, which shows the ratio of the local dynamic pressure over the airfoil to the maximum local dynamic pressure as a function of chordwise position along the airfoil. Also, in figure 6 is a sketch of the airfoil showing the location of the five suction slots. These slots were 1/32 inch in width and were shaped as type D shown in figure 3. The slots were fabricated in the form of brass inserts which fitted into the wooden model flush with the surface.

Boundary-layer measurements were successively made 1/2 inch in front of each slot with all slots ahead of the measuring position in operation in each case. These measurements were made for a range of tunnel speeds and internal suction quantities. The range of Reynolds number, based on the velocity 1/2 inch ahead of slot 1 and the airfoil chord, extended from 5.0×10^6 to 10.0×10^6. The maximum flow rate employed per slot corresponded to a flow coefficient of 0.000105 based on the wing chord and the local velocity 1/2 inch ahead of slot 1. The boundary-layer Reynolds number R_δ 1/2 inch ahead of slot 1 ranged from 3520 to 4510.

Suction Slots in a Favorable Pressure Gradient

In the absence of surface roughness or irregularities and within the range of airspeeds possible with the low-turbulence tunnel, an extensive length of laminar flow is necessary in a region of favorable pressure gradient before boundary-layer transition will occur. For this reason, a symmetrical airfoil of 18-foot chord having an extensive length of favorable pressure gradient was chosen for investigating the use of suction slots as a means of increasing the extent of laminar flow in a region of favorable pressure gradient.

The measured distribution of dynamic pressure expressed as the ratio of the local to the maximum local dynamic pressure is presented in figure 7 for a portion of the model. The peculiar variation of the pressure gradients over the forward part of the airfoil is explained by the fact that the leading edge of the unusually long model extended well into the entrance cone of the tunnel. Because of the unusual model arrangement the airfoil coordinates become rather meaningless and therefore have not been presented. For the same reason, the range of flow conditions corresponding to the variation in tunnel speed cannot be expressed in terms of the usual form of the Reynolds number, and a suction flow coefficient based on free-stream velocity and model chord does not have the usual meaning. Also, the measured extension of laminar flow cannot be thought of as occurring

on a specific airfoil as was the case for the measurements made for an unfavorable gradient. A comparison of the results obtained in the unfavorable and favorable pressure gradients is possible, however, on the basis of the effect of suction slots in increasing the Reynolds number based on the extension of the laminar layer when the boundary-layer Reynolds number ahead of the first slot is about the same for both gradients. For the tests in the favorable pressure gradient, the boundary-layer Reynolds number as measured ahead of slot 1 was varied from 2680 to 3680.

The suction flow was varied individually in each slot and a wide range of flow rate was investigated in an attempt to obtain a maximum of laminar extension for the slot arrangement used.

The location of the suction slots is shown in figure 7. Eight slots of $\frac{1}{32}$-inch width and 10-inch spacing were installed in the lower surface of the model in the same manner as that described for the model used in the investigations of an unfavorable pressure gradient.

The extension in the region of laminar flow produced by the slots was determined by comparing measurements of the transition point on the upper surface of the wing where no slots were installed with measurements of the transition point on the slotted surface. Boundary-layer measurements were made 1/2 inch in front of each slot and, in each case, all of the slots ahead of this point were in operation.

RESULTS AND DISCUSSION

The various investigations were described in some detail in the foregoing section of the paper. The results obtained from these investigations together with some discussion are given in the following pages. The results are considered under the same headings that were employed in the section entitled "Description of Investigations" so that reference can be made readily to the details of the test configurations from which the results were obtained.

Slot Geometry and Arrangement

Types of slot.- As previously mentioned, the design of an optimum type of slot presents the problem of determining the configuration which will require the minimum power for a given flow rate and which will not, in itself, cause transition within the range of

conditions over which it is expected to operate. The problem of slot design for minimum total pressure loss is considered first. The effect of size and shape upon the pressure-loss characteristics of the normal slots is shown in figure 8.

The pressure-loss data for each slot are presented as the ratio of the total pressure loss of the boundary-layer air removed to the dynamic pressure outside the boundary layer at the slot station and are plotted as a function of the flow coefficient ΔC_Q. The data are presented for a range of Reynolds number which, based on the 5-foot model chord, extended from 4.7×10^6 to 8.0×10^6 and the value of ΔC_Q varied from 0 to 0.00025.

In figure 8, no distinction is made between the data obtained for the different Reynolds numbers. In the general case, as shown in the analysis presented in a subsequent section entitled "Slot Pressure Loss Analysis," the flow coefficient ΔC_Q is not sufficient to define the pressure loss for a particular slot. The data as presented in figure 8 are, therefore, important only as an indication of the relative merits of the different types of slots for the particular range of test conditions investigated. In general, this range of test conditions includes those encountered in the investigations of boundary-layer control in favorable and unfavorable pressure gradients.

A consideration of the data of figure 8 indicates that the two slot-shape variables which have the most influence on the pressure loss at constant flow rate are the slot width and the position of the rear wall of the slot. As might have been expected, increasing the width of the slot decreases the pressure loss for a given flow rate. The upward extension of the rear wall of the slot to form a "shoulder," slots A and B, also seems to have a favorable effect on the pressure loss; such an effect stems from a small amount of pressure recovery or "ram" through the slot which is not realized with the flush installation. A wide slot having its rear wall displaced upward would, therefore, seem to be best for small pressure loss. The pressure loss seems to be relatively unaffected by changes in the shape of the slot lips.

Unfortunately, the slot design required for minimum suction power and that required to avoid disturbance of the boundary layer in the external flow are somewhat conflicting. Except for a rather narrow range of tunnel speeds and flow quantities, the widest slots (1/16 inch), which required the least power, proved to be rather unsatisfactory in that turbulence was produced in the boundary layer

at the slots. The width of the $\frac{1}{16}$-inch slot was of the order of twice the boundary-layer thickness δ just ahead of the slot for the range of Reynolds numbers investigated. Flush slots of $\frac{1}{32}$-inch width, the order of magnitude of the boundary-layer thickness, appeared to have no adverse effect upon the laminar layer throughout the range of operating conditions investigated. An upward displacement of the rear wall of the slot had a definitely adverse effect upon the stability of the external flow, as laminar flow could not be maintained downstream of the slot for operating conditions outside a rather narrow range. Variations in the size and shape of the slot lips had little effect upon the stability of operation of any of the slots.

The backward opening slot, the screened slot, and the perforated plate (fig. 4) were all about equally unsatisfactory. The backward opening slot required large amounts of power and the stability of operation seemed very sensitive to flow rate and airspeed. The screened slot and the holes caused transition at the suction position in all cases.

Of all the slots investigated, the flush normal slot having a width of the order of magnitude of the boundary-layer thickness seemed to require the least power without compromise in regard to boundary-layer stability. Although both the power and the stability seemed to be unaffected by the slot-lip shape, it appeared that slot D with a width of 1/32 inch should be inherently more stable than the other slots for two reasons: first, the separation point is definitely established on the upstream face, which means that the separation will not oscillate to produce a disturbance in the external flow, and second, the flow experiences a minimum number of pressure peaks on the rear face of the slot and, as a result, laminar separation is less likely to occur. This type of slot was employed in all of the subsequent investigations. The conclusions obtained from the slot investigation regarding stability of operation are based on tests in which the boundary-layer Reynolds number R_δ ahead of the slot did not exceed approximately 4000. No test data were obtained which could be used to show whether the type of slot which appears satisfactory at a value of R_δ of 4000 is also satisfactory at higher values of R_δ.

Slot spacing.- As previously mentioned, the maintenance of a boundary-layer Reynolds number less than a specified value was believed to be one method of approaching the problem of extending laminar layers by suction. This method of approach raises the problem of determining the manner in which the suction power for a single slot must be varied in order to maintain a given value of R_δ at increasing

distances downstream from the slot. Typical results obtained from the limited investigation of this problem are presented in figure 9. The results are in terms of an airfoil-drag-coefficient equivalent of the suction power required to maintain a boundary-layer Reynolds number of 3500 at various distances behind the slot. The Reynolds number based on the 90-inch chord of the NACA 27-215 airfoil employed in this investigation was 8.1×10^6. The data show that the drag increases nearly linearly with distance for relatively small distances. The maintenance of an R_δ of 3500 for larger distances behind the slot causes a rapid increase in the slope of the curve of drag plotted against distance. This result suggests that a limit exists for the distance through which one slot may be employed efficiently for controlling the boundary-layer Reynolds number and that multiple slots should be employed for greater distances. A general analysis of the conditions controlling the behavior of curves of suction drag plotted against slot spacing, such as those presented in figure 9, is presented in the section entitled "Determination of the Relations Controlling the Distribution of Suction Slots."

Suction Slots in an Unfavorable Pressure Gradient

The results to be discussed concerning the extension of laminar flow in a region of unfavorable pressure gradient were obtained for Reynolds numbers of 5.75×10^6 and 7.5×10^6. As pointed out previously, these Reynolds numbers are based on the chord of the airfoil and the velocity 1/2 inch ahead of slot 1 (fig. 6).

On the plain airfoil without suction, transition corresponding to the beginning of turbulence was found to occur for a Reynolds number of 7.5×10^6 at a point about 6 inches behind the position shown for the first slot in figure 6. At the lower Reynolds number, the transition point occurred somewhat farther back although its location was not clearly shown by the data. With the operation of slot 1 alone, boundary-layer measurements at both Reynolds numbers indicated that laminar flow could be maintained for at least 30 inches behind the slot. The suction power required to maintain laminar flow at this point was relatively small. The corresponding drag-coefficient equivalent of the suction power for a Reynolds number of 7.5×10^6 was 0.00012, and the flow coefficient was 0.000088. These coefficients are based on the airfoil chord and the velocity 1/2 inch ahead of slot 1.

Attempts to obtain further increase in the extent of laminar flow were made with slots 2, 3, and 4 installed in addition to slot 1

(fig. 6). A number of boundary-layer profiles obtained at various positions on the airfoil surface with different numbers of slots in operation are shown in figure 10. For the different positions at which measurements were made, one boundary-layer profile is presented for each of the two Reynolds numbers 5.75×10^6 and 7.5×10^6. In each case, the profiles presented were chosen from the available data so that the ratio of the total flow removed through the slots to the total flow in the boundary layer 1/2 inch ahead of slot 1 $\Sigma\Delta Q/Q_{b_l}$ was the same for the two Reynolds numbers. The flow quantity removed at each slot and the total amount of flow removed are indicated for both Reynolds numbers in the figures. The flow quantities are expressed as the product of the flow coefficient C_Q and the square root of the airfoil-chord Reynolds number R, since constancy of the parameter $C_Q\sqrt{R}$ is sufficient to insure that the value of $\Sigma\Delta Q/Q_{b_l}$ is the same at a given point on the same airfoil at various Reynolds numbers. Also shown in each figure for comparison is the Blasius flat-plate profile which has the same thickness as the experimental profile measured at the highest Reynolds number.

The boundary-layer profiles for a position 1/2 inch ahead of slot 3, with slots 1 and 2 in operation, are shown in figure 10(a). The profiles for both Reynolds numbers appear to be laminar in character. In comparison with the Blasius flat-plate profile, however, the experimental profiles seem to be somewhat curved such that the velocities are relatively higher near the surface. This curvature seems to be greatest for the higher Reynolds number case. Corresponding variations in the flow rate in slots 1 and 2 for the two Reynolds numbers did not alter this comparison.

In figures 10(b) and 10(c) are shown the profiles obtained at distances of 10 and 15 inches behind slot 3 with slots 1, 2, and 3 in operation. For the lower Reynolds number, the profiles for both positions are unquestionably laminar and do not differ very much from the Blasius type. At the higher Reynolds number, however, the character of the flow cannot easily be ascertained from the boundary-layer measurements because the profiles are curved in the manner already noted ahead of slot 3, but to a greater extent and by an amount which increases with distance behind the slot. The curvature of the profiles as the velocity approaches zero seems more characteristic of a turbulent rather than laminar boundary layer; however, the thicknesses of the boundary layers shown in figures 10(b) and 10(c) do not seem nearly so large as would be expected in the case of fully developed turbulence. On the other hand, the profiles obtained do not seem characteristic of the usual type of laminar profiles that would be expected to occur in an unfavorable pressure gradient. An

examination of the boundary-layer equations (reference 7) indicates that in an unfavorable pressure gradient the curvature of the velocity profile near the surface would approach that which is characteristic of a separation profile. The large distance between the slot and the point of measurement would seem to preclude the possibility of the observed type of curvature being caused by suction.

One possible explanation for the observed behavior of the boundary-layer profiles at the higher Reynolds number can be found if a regular, rather large-scale, oscillation of the laminar boundary layer is assumed. Such an oscillation could be initially induced by turbulence in the free stream or by some disturbance on the surface of the model such as could be introduced by imperfections in the surface or possibly by the flow of the boundary layer across the slots themselves. Since the profile velocities within the boundary layer were determined from measurements of the mean dynamic pressure, the indicated velocities in an oscillating flow would be higher than the actual mean velocities. This effect at any point in the flow would come about because the mean of the maximum and minimum dynamic pressures resulting from the oscillations would not correspond to the dynamic pressure calculated from the mean velocity. The percentage error would, of course, decrease as the mean velocity increases if the magnitude of the perturbation velocity were the same at all points throughout the boundary layer. An oscillating boundary layer or an oscillation within the lower region of the boundary layer could thus account for the observed curvature in the velocity profiles. This seemingly plausible explanation, however, can be substantiated or disproved only by further research. Such research could probably be conducted most profitably with the use of the hot-wire anemometer.

If the presence of an oscillating boundary layer is assumed to explain the observed curvature of the profiles, the question arises as to whether, as the flow progresses, these oscillations will increase in magnitude and eventually cause the boundary-layer flow to break up into the random eddies characteristic of the usual type of turbulent motion. For certain oscillation frequencies and within a certain range of Reynolds number, the magnitude of a disturbance is known to increase as the flow progresses and to cause eventual transition. (See, for example, reference 8.) Since the data obtained for distances of 10 and 15 inches behind slot 3 seem to indicate that the disturbance is increasing in magnitude, actual turbulent flow might be expected to occur at some distance farther downstream.

In an attempt to overcome the seemingly undesirable curvature characteristics of the boundary layer as measured between slots 3 and 4, an additional suction slot (slot 3a) was installed ahead of slot 4 at a distance of 12.5 inches behind slot 3 (fig. 6). With

slots 1, 2, 3, and 3a in operation, measurements of the boundary layer were made at a position 1/2 inch ahead of slot 4 (fig. 10(d)); and, with slot 4 in operation in addition to the other four slots, measurements were made at distances of 10 and 15 inches behind slot 4 (figs. 10(e) and 10(f)). When a comparison is made between the data obtained at a position 1/2 inch ahead of slot 4 with slots 1, 2, 3, and 3a in operation (fig. 10(d)) and the data obtained at a position 15 inches behind slot 3 with slots 1, 2, and 3 in operation (fig. 10(c)), the addition of slot 3a is seen to decrease somewhat the curvature of the profiles at the higher Reynolds number which would seem to indicate a decrease in magnitude of the assumed oscillation. The measurements 10 inches behind slot 4 (with all five slots in operation) indicate that, at the higher Reynolds number, the assumed oscillation may have grown in magnitude, as shown by the increased curvature of the profile near the surface (fig. 10(e)). At a position 15 inches behind slot 4, the data show a large amount of curvature in the profiles for both Reynolds numbers. Although the thickness of these profiles does not appear to be as great as might be expected for a fully developed turbulent boundary layer, their shape seems much more characteristic of turbulent than laminar profiles. Perhaps, the measurements were made at a position where the small-scale random eddies characteristic of the usual type of turbulent motion are just beginning to develop in the lower portion of the boundary layer.

As previously pointed out, it is impossible without further research to state with certainty the type of flow that existed in the boundary layer at the higher Reynolds number. The hypothesis of an oscillation in the laminar layer seems to be the only plausible explanation for the experimentally observed behavior of the boundary layer at the higher Reynolds number. In the absence of additional information concerning the observed phenomenon, the assumption will be tentatively made that the concept of an oscillating laminar layer explains the experimental results. On the basis of this assumption, then, the data indicate that, by the use of suction slots, laminar flow was extended from a position 6 inches behind slot 1 to a position at least 10 inches behind slot 4 (a laminar extension of 0.52 of the chord) for a Reynolds number based on local velocity 7.5×10^6 and with a boundary-layer Reynolds number 1/2 inch ahead of slot 1 of 4510. This increase in the length of laminar flow corresponds to a Reynolds number of 3.84×10^6. The flow coefficient required to accomplish this result was 0.00026 for one surface of the airfoil. For the purpose of evaluating the suction flow in terms of the laminar extension, a useful suction coefficient may be obtained by dividing the quantity of suction by the distance through which the laminar layer was extended and the local velocity on the airfoil at the point of transition without suction. This type of coefficient is particularly helpful in comparing the relative effectiveness of slots in

unfavorable and favorable pressure gradients. The value of this coefficient for the 0.52–chord extension of the laminar boundary layer at the higher Reynolds number was 0.00051 for one surface of the airfoil.

Because the exact position of transition without suction was not definitely established at a Reynolds number of 5.75×10^6, no detailed evaluation of the over-all effect of the boundary-layer control is possible for this lower Reynolds number case. The maximum linear extension of the region of laminar flow, however, was of the same order for both Reynolds numbers.

The drag-coefficient equivalent of the suction power required to realize the maximum extension in the region of laminar flow at the higher Reynolds number 7.5×10^6 was 0.00031 for one surface. For a more nearly optimum slot spacing, the same extension in laminar flow could probably be achieved with the expenditure of even smaller amounts of suction power. Although drag measurements were not made, the saving in wake drag resulting from the large extension of the region of laminar flow is probably several times greater than the drag equivalent of the boundary-layer-control suction power. The Reynolds number to which this saving corresponds, 7.5×10^6, is, of course, based on the local velocity 1/2 inch ahead of slot 1 and not on the free-stream velocity. If, however, the pressure coefficient at a point 1/2 inch ahead of slot 1 were taken to be about 1.2 for the airfoil under free-air conditions (reference 9), the corresponding free-stream Reynolds number would be 6.85×10^6, and the values of C_Q and c_{d_s} would be 0.000285 and 0.000372, respectively. This Reynolds number is considerably higher than that for which any net drag savings were obtained either by Pfenninger (reference 3) or Holstein (references 1 and 2).

In the present investigation, however, laminar flow could not be maintained much beyond the position of slot 2 when the Reynolds number, based on the velocity 1/2 inch ahead of slot 1, was increased to 9.5×10^6, nor could laminar flow be extended beyond a position 10 inches behind slot 4 at any of the Reynolds numbers considered. On the basis of the preceding discussion, the difficulties apparently arose as a result of the amplification of small disturbances introduced into the boundary layer. The possible source of these disturbances is not entirely clear. Imperfections in the surface condition, the effect of the slots themselves, or possibly excessive free-stream turbulence must all be considered as possible sources of the

disturbances. In regard to these sources of disturbance, it was found that, unless the very greatest care was exercised in keeping the surfaces of the model in an extremely smooth condition, no increases in laminar flow could be obtained with suction through the slot arrangement tested. Also, free-stream turbulence of appreciable magnitude was known to exist in the wind tunnel at the time of the tests. The effect on the external boundary-layer flow of removing air through the slots undoubtedly constituted a source of disturbance, although the magnitude of the effect is not known. Perhaps, a smaller slot spacing and a correspondingly smaller suction quantity at each slot would be a more favorable arrangement than that employed in this investigation.

Much more research is therefore necessary before any conclusions can be reached regarding the practical effectiveness of suction slots as a means of extending the laminar layer in regions of unfavorable pressure gradient at flight values of the Reynolds number and for surface conditions corresponding to those encountered in practical flight operations.

Suction Slots in a Favorable Pressure Gradient

Although the range of data obtained in the investigation of suction slots in a favorable pressure gradient was rather extensive, the useful results which can be derived from these data are rather limited. Measurements of the transition point on the upper surface of the symmetrical model (the slots were on the lower surface) were made at two different tunnel airspeeds. At the highest tunnel speed, transition on the upper surface was found at a point 40 inches behind the station of the first slot. (See fig. 7.) The flat-plate Reynolds number which would give the same boundary-layer Reynolds number as that measured just before transition was 5.3×10^6. When the tunnel speed was reduced by about 25 percent, the transition point on the upper surface was observed at a station corresponding to 52 inches behind the position of the first slot, and the equivalent flat-plate Reynolds number corresponding to the Reynolds number of the measured laminar boundary-layer profile was 5.2×10^6.

With the first six slots operating, transition on the lower surface was observed to occur at a point 60 inches behind the first slot (1/2 inch ahead of slot 7, see fig. 7) at the highest tunnel airspeed. Neither increasing the amount of suction through slots 1

to 6 nor applying suction in large amounts to slots 7 and 8 resulted in any farther rearward movement of the transition point. The increase in laminar flow in terms of a Reynolds number based on the velocity at the transition point without boundary-layer control was 2.6×10^6 and the boundary-layer Reynolds number 1/2 inch ahead of the first slot was 3680 for the condition of high tunnel speed. At the lower tunnel speed, suction through the first seven slots moved transition to a point 70 inches behind the first slot (1/2 inch ahead of slot 8, fig. 7). By no combination of suction through all eight slots was it possible to move the transition point any farther rearward. With the use of seven slots at the lower airspeed, the increase in the extent of laminar flow corresponded to a Reynolds number of 1.9×10^6 and the boundary-layer Reynolds number 1/2 inch ahead of the first slot was 2680.

Because of the nature of the test setup employed in this particular investigation, the quantity of flow required to achieve the results just discussed cannot be expressed in the form of the usual flow coefficient C_Q. In order to give some idea of the flow involved, however, a flow coefficient based on the velocity at the transition point without suction and on the length through which the laminar layer was extended by suction may be used as an indication of the merits of suction in extending the laminar boundary layer in a given velocity field. Such a flow coefficient for the high-speed case was 0.00115 and for the low-speed case 0.000312. Corresponding measurements of the total pressure loss were not made for this particular test.

From the results presented, some increases in the extent of laminar flow in a region of favorable pressure gradient are seen to be possible by the use of suction slots. The maximum increases in the extent of laminar flow obtained in the present tests in a favorable pressure gradient, however, seem relatively small when compared with the results obtained in an unfavorable pressure gradient.

For example, the maximum extension in laminar flow obtained in tests in a favorable pressure gradient was, when expressed as a Reynolds number, only about two-thirds of that obtained in the unfavorable pressure gradient (2.6×10^6 as compared with 3.84×10^6); whereas the necessary flow coefficient in the favorable pressure gradient was about twice that in the unfavorable pressure gradient (0.00115 as compared with 0.00051). This result is contrary to what would normally be expected. An explanation for this result seems particularly difficult when it is considered that the boundary-layer Reynolds number at the outset of suction (ahead of slot 1) was greater for the unfavorable gradient than for the

favorable gradient. From measurements of the boundary layer near the position of transition with the slots in operation, the profiles in the favorable pressure gradient were observed, however, to have the same curved shape near the surface that was discussed in the previous section of this paper devoted to suction slots in an unfavorable pressure gradient. From this observation, the extent of laminar flow might be assumed to be limited by disturbances initiated by free-stream turbulence, surface imperfections, or perhaps by the slots themselves. It is not at all impossible that such disturbances may have been relatively more severe in the experiments with the favorable gradient than in those with the unfavorable gradient.

The conclusions to be reached from these tests are the same as those discussed in the section on suction slots in an unfavorable pressure gradient; more research is necessary before definite conclusions regarding this type of boundary-layer control can be reached.

DETERMINATION OF THE RELATIONS CONTROLLING THE DISTRIBUTION OF SUCTION SLOTS

As previously pointed out, one of the purposes of suction slots is to limit the growth of the boundary layer so that the boundary-layer Reynolds number for transition is never exceeded. The purpose of the analysis to be presented is to determine and relate the parameters controlling the drag required to maintain a chosen boundary-layer Reynolds number at various distances behind a slot so that the optimum slot spacing for any particular application may be determined.

The drag-coefficient equivalent of the suction power for a particular slot depends upon the quantity of flow removed through the slot and the total pressure lost by the flow passing through the slot. The analysis is concerned, first, with the manner in which the suction flow quantity necessary to maintain a given boundary-layer Reynolds number at different distances behind a slot varies with these distances and, second, with the manner in which the pressure loss through the slot depends upon the quantity of flow removed and the geometry of the slot and flow field.

Slot Quantity-Flow Analysis

If, in figure 11, numbers 1, 2, and 5 represent stations just before and after a slot and at some distance l downstream of the slot,

then the problem is to determine the quantity of flow that must be removed by the slot between stations 1 and 2 so that $R_{\delta_5} = R_{\delta_1}$; that is, the ratio $R_{\delta_1}/R_{\delta_2}$ must be such that the growth in R_δ through the distance l will result in $R_{\delta_1} = R_{\delta_5}$. The relationship between these various parameters will be investigated by use of the Blasius relations for the boundary-layer flow over a flat plate. The use of the Blasius relations permits a discussion of the fundamental aspects of the problem without undue mathematical complication and with a fair degree of quantitative accuracy for airfoils having small pressure gradients. The use of an equation for the boundary-layer growth which involves the pressure gradient may be desirable for determining the slot spacing on an actual airfoil; however, the fundamental problem is the same as that described in the following discussion.

The Blasius relationship for the case in which δ is defined as the distance normal to the surface at which $\frac{u}{U} = 0.707$ can be written in the following form (somewhat different from that given in reference 7):

$$\frac{x'}{c} = \frac{1}{5.29} \frac{R_\delta{}^2}{R} \tag{1}$$

where x' is the distance required for the boundary layer to grow to the value R_δ, c is the complete chord of the flat plate, and R is the Reynolds number based on the complete chord and the velocity on the plate. The value of δ used, as throughout the present paper, is that corresponding to $\frac{u}{U} = 0.707$. The distance l is then equal to $x_5' - x_2'$ where x_5' and x_2' are the equivalent distances which would be required for the boundary-layer Reynolds number to grow to values of R_{δ_5} and R_{δ_2}, respectively. (See fig. 11.) Consequently, l/c can be expressed in the following form:

$$\frac{l}{c} = \frac{R_{\delta_5}{}^2}{5.29R}\left[1 - \left(\frac{R_{\delta_2}}{R_{\delta_5}}\right)^2\right] \tag{2}$$

and since suction will be used to hold $R_{\delta_5} = R_{\delta_1}$, equation (2) may

be written as

$$\frac{l}{c} = \frac{{R_{\delta_1}}^2}{5.29R}\left[1 - \left(\frac{R_{\delta_2}}{R_{\delta_1}}\right)^2\right] \tag{3}$$

Equation (3) gives the relation between the chord Reynolds number R and the reduction in R_δ required across a slot in order to cause the value of R_δ in front of the slot to reoccur at some distance l downstream of the slot. This equation, however, does not fulfill the requirements since a relation between l/c, R, R_{δ_1}, and the quantity of flow removed is desired.

In the course of the experimental investigations previously described, a rather large number of boundary-layer measurements were made 1/2 inch in front and 1/2 inch behind a slot for various amounts of suction. These data have been correlated to show the reduction in R_δ across a slot, expressed in the form $R_{\delta_2}/R_{\delta_1}$, as a function of the flow removed. The parameter used to describe the flow removed is the ratio of the quantity of flow sucked off to the total flow in the boundary layer just ahead of the slot. The actual flow removed was determined experimentally as previously described. The total quantity of flow in the boundary layer per unit span Q_{bl} was determined in the following way:

$$Q_{bl} = U(\delta_{0.997} - \delta^*)$$

where U is the velocity just outside the boundary layer at the slot, $\delta_{0.997}$ is the boundary-layer thickness corresponding to the position above the airfoil surface at which $\frac{u}{U} = 0.997$, and δ^* is the displacement thickness. Since $\delta_{0.997}$ and δ^* for Blasius flow are given by (reference 7)

$$\delta_{0.997} = \frac{5.53x'}{\sqrt{R_{x'}}}$$

$$\delta^* = \frac{1.73x'}{\sqrt{R_{x'}}}$$

the quantity of flow can be expressed as

$$Q_{bl} = \frac{3.80Ux'}{\sqrt{R_{x'}}}$$

and by multiplying numerator and denominator by the kinematic viscosity ν

$$Q_{bl} = 3.80\nu\sqrt{R_{x'}}$$

When δ is defined as that distance above the surface at which $\frac{u}{U} = 0.707$,

$$\sqrt{R_{x'}} = \frac{R_\delta}{2.31}$$

Therefore,

$$Q_{bl} = 1.65\nu R_\delta \tag{4}$$

The quantity of flow in the boundary layer was calculated according to equation (4) by the use of the experimentally determined values of R_δ just ahead of the slot and the appropriate value of ν.

In determining the values of the ratio $R_{\delta_2}/R_{\delta_1}$ from the experimental data, the value of R_{δ_1} for the zero-suction-flow condition was used in all cases. Comparative measurements of the boundary layer just in front of and behind the slot showed that the boundary-layer profiles tended to change shape in passing across the slot. This effect was noted even for the case of zero flow within the slot. Measurements at short distances behind the slot, however, indicated that the profile shape quickly reverted to the Blasius type. In order for the relation between $\Delta Q/Q_{bl}$ and $R_{\delta_2}/R_{\delta_1}$ to have any

significance in this analysis, the boundary-layer shapes from which R_{δ_1} and R_{δ_2} are determined must be the same. The distorted profiles measured directly behind the slot were therefore converted to equivalent Blasius profiles. This conversion was made by first calculating the Reynolds number based on the boundary-layer momentum thickness R_θ from the experimental profiles obtained behind the slot. The relation between R_θ and R_δ for a Blasius velocity distribution can be shown from reference 7 to be

$$R_\delta = 3.48R_\theta \tag{5}$$

The equivalent values of R_δ were then obtained by substituting the experimental values of R_θ in equation (5).

The ratio of R_{δ_2} to R_{δ_1} is shown in figure 12 as a function of $\Delta Q/Q_{bl}$. The relation between $R_{\delta_2}/R_{\delta_1}$ and $\Delta Q/Q_{bl}$ is seen to be linear and is given by the following expression:

$$\frac{R_{\delta_2}}{R_{\delta_1}} = 1 - 1.60\frac{\Delta Q}{Q_{bl}} \tag{6}$$

The values of $\Delta Q/Q_{bl}$ for which the relation (6) was determined do not extend beyond 0.275. Extreme care should be exercised in employing equation (6) for higher values of $\Delta Q/Q_{bl}$ because a consideration of the physical boundary condition that $R_{\delta_2}/R_{\delta_1}$ must approach a value near zero when $\Delta Q/Q_{bl}$ is 1.0 indicates that the slope constant 1.60 in equation (6) must change at some value of $\Delta Q/Q_{bl}$ higher than that for which data are available.

Equation (6), in combination with equation (3), provides the desired relation between the boundary-layer Reynolds number ahead of the slot R_{δ_1}, the airfoil-chord Reynolds number R, the distance l required for the boundary-layer Reynolds number to grow back

to the value R_{δ_1}, and the quantity of flow removed. The final equation obtained by substituting the expression for $R_{\delta_2}/R_{\delta_1}$ into equation (3) is as follows:

$$\frac{l}{c} = \frac{0.48{R_{\delta_1}}^2}{R}\left[1.25\frac{\Delta Q}{Q_{bl}} - \left(\frac{\Delta Q}{Q_{bl}}\right)^2\right] \qquad (7)$$

If equation (7) is to be used for estimating the growth in R_δ on an airfoil section, R must be based on the airfoil chord and some appropriate value of the velocity on the airfoil surface, for example, the velocity ahead of the particular slot for which calculations are being made.

In order to illustrate the nature of such a function as equation (7), $\Delta Q/Q_{bl}$ has been plotted against l/c in figure 13 for a constant value of $\frac{0.48{R_{\delta_1}}^2}{R}$ of 1.0. The curve shows that for values of $\Delta Q/Q_{bl}$ less than 0.15, the variation of l/c with $\Delta Q/Q_{bl}$ is almost linear. Thus, if within this near-linear range it is desired to maintain a given R_δ at some distance l/c downstream of a slot, the total $\Delta Q/Q_{bl}$ required will be about the same regardless of whether this amount of flow is removed at one slot or small amounts of flow are removed from a number of slots distributed over the distance l/c. If the value of l/c is sufficiently large so that the variation of l/c with $\Delta Q/Q_{bl}$ is appreciably nonlinear, some reduction in the total necessary suction flow quantity will occur if the removal is accomplished by sucking off relatively small amounts of flow through several slots. In general, if the total amount of suction flow is to be kept at a minimum, the slot spacing for a particular set of conditions should be no greater than the largest value of l/c corresponding to the limit of the nearly linear variation of l/c with $\Delta Q/Q_{bl}$. As previously stated, the plot of figure 13 is for a value of the parameter $\frac{0.48{R_{\delta_1}}^2}{R}$ of 1.0. Variations in the relative values of R_{δ_1} and R, of course, change the slope of the curve of l/c plotted against $\Delta Q/Q_{bl}$. Reductions

in the value of R_{δ_1} relative to R cause a rapid decrease in the slope of the curve of l/c plotted against $\Delta Q/Q_{bl}$ such that the value of l/c corresponding to the limit of the nearly linear variation of l/c with $\Delta Q/Q_{bl}$ decreases. This decrease means, of course, that if a given value of R_{δ_1} is to be maintained on an airfoil section, the slot spacing should decrease with increasing wing Reynolds number if the value of $\Delta Q/Q_{bl}$ is not to increase. It is quite obvious that if a given slotted airfoil is operated at Reynolds numbers higher than those for which it is designed, a constant value corresponding to the design condition of the ratio ${R_{\delta_1}}^2/R$ rather than a constant value of R_{δ_1} must be maintained if the total flow removed is not to be excessive.

Since equation (7) was derived through the use of the relations for the boundary-layer flow on a flat plate, care should be exercised in applying it to airfoil sections having large pressure gradients. For such applications, the data of figure 12 relating $\Delta Q/Q_{bl}$ and $R_{\delta_2}/R_{\delta_1}$ should be used in conjunction with an expression for the boundary-layer growth which involves the pressure gradient. In order to give some indication of the applicability of the method developed through the use of the flat-plate boundary-layer theory, computations of the variation of $\Delta Q/Q_{bl}$ with l/c have been made according to equation (7) and the data of figure 12 for an airfoil on which corresponding experimental data are available. Results have already been presented which show the manner in which the drag-coefficient equivalent of the suction power required to maintain a given R_δ varies with distance behind the slot (fig. 9). From these data the corresponding variation of $\Delta Q/Q_{bl}$ with distance has been determined and is shown in figure 14(a). The free-stream airfoil-chord Reynolds number R was 8.1×10^6 and the value of R_δ which was maintained at various distances downstream was 3420. The pressure distribution about the airfoil is shown in figure 5. The Reynolds number R employed in equation (7) is based on the airfoil chord and the local velocity just ahead of the slot. The results of the computations made according to equation (7) and figure 12 are shown as the dashed curve in figure 14(a). Some discrepancy exists between the theoretical and experimental results; however, in view of the approximations made in the theoretical analysis, the agreement between theory and experiment seems to be fairly reasonable.

Although the variation of the required $\Delta Q/Q_{bl}$ with l/c has been investigated, the ultimate aim of this analysis is to provide a method for determining the variation with l/c of the drag equivalent of the suction power. The following section is, therefore, devoted to an analysis of the parameters that control the total pressure loss in the suction slot.

Slot Total-Pressure-Loss Analysis

In analyzing the total pressure losses existing in air that has been removed by a boundary-layer suction slot, proper consideration of the effect of slot design would seem to require that the losses be considered in two parts. One part of the loss, evidenced as a velocity defect in that portion of the boundary layer to be removed, would exist independent of the slot, and the other part of the loss is, of course, imposed on the suction air because of the inefficiency of the slot. Thus, the combined loss may be written as

$$\Delta H = \Delta H_{bl} + \Delta H_{slot} \tag{8}$$

Since the static pressure through the boundary layer is essentially constant, the total pressure loss in that portion of the boundary layer which is removed ΔH_{bl} can be considered as the difference between q, the local dynamic pressure outside the boundary layer, and $\bar{q}_1$, the integrated mean of the dynamic pressure of the air to be removed at station 1 immediately ahead of the slot (see fig. 11); that is,

$$\Delta H_{bl} = q - \bar{q}_1$$

Equation (8) may then be written as

$$\frac{\Delta H}{q} = 1 - \frac{\bar{q}_1}{q} + \frac{\Delta H_{slot}}{q} \tag{9}$$

The losses in the slot are considered to be associated with the effects of friction, and possibly separation within the slot, and with the sudden dumping of the suction air into the large collector (see fig. 11). The basic assumption is made that these losses vary in

proportion to a mean dynamic pressure $\bar{q}_3$ within the slot entrance

$$\Delta H_{slot} = C_1\bar{q}_3 \tag{10}$$

The dynamic pressure within the slot $\bar{q}_3$ is defined as $\frac{1}{2}\rho\left(\frac{\Delta Q}{w}\right)^2$, where ΔQ is the quantity of flow removed per unit span and w is the slot width. Because of the effects of boundary-layer shape ahead of the slot, the angle between the slot and external surface, and the change in the suction-flow stream tube in passing from the external boundary layer into the slot, the distribution of velocity at any station within the slot is probably nonuniform. Inasmuch as this analysis is concerned with a single-slot surface angle, slot inlet radius (slot D_1, fig. 8), and velocity distribution ahead of the slot (essentially a Blasius flat-plate profile), the variation of the distribution of velocity within the slot would appear to depend primarily on the change in the suction stream tube. For the conditions under consideration, the geometry of the suction stream tube can be fairly well represented by the ratio of the height of the layer to be removed to the slot width h/w. (See fig. 11.) The value of the coefficient C_1 in equation (10) would therefore be expected to vary as a function of the stream-tube geometry parameter h/w. Equation (10) can therefore be written as

$$\Delta H_{slot} = f\left(\frac{h}{w}\right)\bar{q}_3 \tag{11}$$

and, in turn, equation (9) as

$$\frac{\Delta H}{q} = 1 - \frac{\bar{q}_1}{q} + f\left(\frac{h}{w}\right)\frac{\bar{q}_3}{q} \tag{12}$$

In view of the analysis presented in a foregoing section of this paper which related the quantity of flow removed from the boundary layer to the reduction in boundary-layer Reynolds number at a slot, it would be convenient to express equation (12) in terms of the flow removed ΔQ, the total flow in the boundary layer Q_{bl}, the boundary-layer thickness δ, and the slot width w. Before equation (12) can be put into another form, however, an expression must be obtained for the boundary-layer profile ahead of the slot. Experiment has shown that a laminar profile in a region of moderate

pressure gradient can be closely approximated by a Blasius velocity distribution. In the remaining portion of this analysis, the boundary-layer profiles ahead of a slot are therefore considered as being defined by a Blasius velocity distribution. For this type of profile, the velocity in the inner portion of the boundary layer is given as a function of distance from the surface by the following equation (reference 7):

$$u = 0.332Uy\sqrt{\frac{U}{\nu x'}} \tag{13}$$

and, as shown in the preceding section, the total flow in the boundary layer out to a value of u/U equal to 0.997 is given by

$$Q_{bl} = \frac{3.80U}{\sqrt{\frac{U}{\nu x'}}} \tag{14}$$

By the use of equations (13) and (14), the parameter $\bar{q}_1/q$ in equation (12) may now be related to the proportion of the total boundary layer removed $\Delta Q/Q_{bl}$. The quantity of flow removed may be written as

$$\Delta Q = \int_0^h u\, dy \tag{15}$$

and the average kinetic-energy level of the air removed $\bar{q}_1$ may be written as

$$\bar{q}_1 = \frac{\int_0^h \frac{\rho}{2}u^3\, dy}{\Delta Q} \tag{16}$$

By substituting equation (13) in equation (15) and integrating, the following expression is obtained

$$\Delta Q = 0.332U\sqrt{\frac{U}{\nu x'}}\,\frac{h^2}{2} \tag{17}$$

where h does not extend beyond the region in which U varies in a nearly linear manner with y. By use of equations (13) and (16), the expression for the mean dynamic pressure $\bar{q}_1$ is given by

$$\bar{q}_1 = \rho(0.332)^2 U^2 \left(\frac{U}{\nu x'}\right) \frac{h^2}{4} \tag{18}$$

The following equation is obtained by rearranging equation (18) and multiplying the numerator and denominator by U

$$\frac{\bar{q}_1}{q} = \left(0.332U \sqrt{\frac{U}{\nu x'}} \frac{h^2}{2}\right)\left(\frac{0.332}{U} \sqrt{\frac{U}{\nu x'}}\right) \tag{19}$$

A comparison of equation (19) with equations (14) and (17) shows that

$$\frac{\bar{q}_1}{q} = 1.26 \frac{\Delta Q}{Q_{bl}} \tag{20}$$

The parameter $\bar{q}_3/q$ in equation (12) also suggests some sort of relation involving the flow in the boundary layer and the flow removed. The dynamic pressure $\bar{q}_3$ has been defined as

$$\bar{q}_3 = \frac{1}{2}\rho\left(\frac{\Delta Q}{w}\right)^2$$

therefore,

$$\frac{\bar{q}_3}{q} = \frac{\frac{\rho}{2}\left(\frac{\Delta Q}{w}\right)^2}{\frac{\rho}{2}U^2} = \left(\frac{1}{w}\right)^2\left(\frac{\Delta Q}{Q_{bl}}\right)^2\left(\frac{Q_{bl}}{U}\right)^2 \tag{21}$$

The boundary-layer thickness defined as the height above the surface at which $\frac{u}{U} = 0.707$ is given by

$$\delta = \frac{2.31}{\sqrt{\frac{U}{\nu x'}}} \tag{22}$$

and the total flow in the boundary layer is given by equation (14). Hence,

$$\frac{Q_{bl}}{U} = \frac{3.80}{2.31}\delta_1$$

and equation (21) can be written as

$$\frac{\bar{q}_3}{q} = 2.71\left(\frac{\delta_1}{w}\right)^2\left(\frac{\Delta Q}{Q_{bl}}\right)^2 \tag{23}$$

where δ_1 is, of course, the boundary-layer thickness just ahead of the slot.

The remaining quantity in equation (12) $f(h/w)$ may be expressed in terms of $\Delta Q/Q_{bl}$ and δ_1/w by solving equation (17) for h^2

$$h^2 = \frac{2\Delta Q}{0.332U\sqrt{\frac{U}{\nu x'}}}$$

$$= \frac{2\Delta Q}{\frac{0.332}{\sqrt{\frac{U}{\nu x'}}}\frac{U^2}{\nu x'}}$$

and from equations (14) and (22)

$$h^2 = 4.29 \frac{\Delta Q}{Q_{bl}} \delta_1{}^2$$

or

$$\left(\frac{h}{w}\right)^2 = 4.29 \frac{\Delta Q}{Q_{bl}} \left(\frac{\delta_1}{w}\right)^2$$

By the use of equations (20) and (23), equation (12) may now be written as

$$\frac{\Delta H}{q} = 1 - 1.26 \frac{\Delta Q}{Q_{bl}} + K_d \left(\frac{\Delta Q}{Q_{bl}} \frac{\delta_1}{w}\right)^2 \tag{24}$$

where K_d is the slot total-pressure-loss coefficient and is expressed as

$$K_d = f\left(\frac{h}{w}\right) = f\left[\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta_1}{w}\right)^2\right] \tag{25}$$

which, in combination with equation (24), suggests the possibility of the variation of K_d being determined from a variety of slot-pressure-loss data. The significance of the subscript d on the slot coefficient K will be obvious subsequently.

During the course of the previously described investigations of suction slots in unfavorable and favorable pressure gradients, a large amount of slot data was obtained. These data include measurements of the slot pressure loss for a range of flow rates and boundary-layer thicknesses just ahead of the slot. The values of $\Delta Q/Q_{bl}$ and δ_1/w for which pressure-loss data were obtained extended from 0 to 0.3 and from 1.5 to 0.6, respectively. From these data and equation (24), values of K_d were determined for a wide variety of test conditions. The values of K_d so determined are plotted with logarithmic coordinates in figure 15 as a function

of h/w expressed as $\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta_1}{w}\right)^2$. Although there is some random dispersion in the data, the correlation seems rather good. For a given value of $\Delta Q/Q_{bl}$ and δ_1/w, the total pressure loss of the air to be withdrawn through a slot may now be calculated by using equation (24) and the relation given in figure 15 for K_d. The limiting conditions which must be placed on the use of this method are that the slot be of the type considered herein, the boundary-layer profile ahead of the slot be of the Blasius type, and the values of $\Delta Q/Q_{bl}$ and δ_1/w not exceed the limits of those investigated. This last condition is not as restrictive as might appear, since it has been shown in preceding sections of the paper that δ_1/w should be of the order of 1.0 and that $\Delta Q/Q_{bl}$ should be limited to relatively small values.

The manner in which the required value of $\Delta Q/Q_{bl}$ at a particular slot varies with the distance to a point downstream of the slot at which it is desired to maintain a given value of R_δ has already been discussed. In designing an airfoil to operate with suction slots under given conditions, however, the variation of $\Delta Q/Q_{bl}$ with distance is not of the greatest interest, but rather the corresponding variation of the slot pressure loss with distance. Although equation (24), together with the correlation of figure 15, permits the evaluation of the suction-slot pressure loss in terms of $\Delta Q/Q_{bl}$ and conditions just ahead of the slot, the rather complicated relations between δ_1/w and $\Delta Q/Q_{bl}$, expressed in equations (24) and (25), make visualization of the slot-loss variation with these parameters difficult. As an outcome of the observation that, on logarithmic coordinates, K_d varies in an almost linear manner with $\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta_1}{w}\right)^2$, the relations between $\frac{\Delta Q}{Q_{bl}}$, $\frac{\delta_1}{w}$, and the slot total pressure loss have been simplified somewhat. The equilateral hyperbola defined by the equation

$$K_h\left[\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta}{w}\right)^2\right] = 2.26 \qquad (26)$$

was found to coincide with the curve of K_d against $\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta}{w}\right)^2$ for low values of $\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta_1}{w}\right)^2$. If a new coefficient K is defined as

$$K = \frac{K_d}{K_h}$$

then, by combining this equation with equation (26)

$$K_d = \frac{2.26}{\left(\frac{\Delta Q}{Q_{bl}}\right)\left(\frac{\delta_1}{w}\right)^2}K$$

and equation (24) may be rewritten as

$$\frac{\Delta H}{q} = 1 + \frac{\Delta Q}{Q_{bl}}\left(2.26K - 1.26\right) \tag{27}$$

Equation (27) shows that $\Delta H/q$ varies linearly with $\Delta Q/Q_{bl}$ as long as K has a value of 1.0. The parameter K is plotted in figure 16 as a function of $\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta_1}{w}\right)^2$, and the value of K can be seen to be, indeed, 1.0 for a short range of values of $\frac{\Delta Q}{Q_{bl}}\left(\frac{\delta_1}{w}\right)^2$.

In choosing an optimum slot spacing for an airfoil section, the form of equation (27) and figure 16 becomes particularly convenient. The preceding analysis presented on suction-flow requirements has shown under what conditions the value of $\Delta Q/Q_{bl}$ required to maintain a given R_δ at various distances downstream of the slot varies almost linearly with distance. If, within this linear range, a value of $\Delta Q/Q_{bl}$ is selected such that, together with the given boundary-layer thickness ahead of the slot, the value of K in equation (27) is 1.0, then $\Delta H/q$ will vary linearly with distance up to that

position corresponding to the limiting value of $\Delta Q/Q_{bl}$ for $K = 1.0$. If a slot spacing any greater than this distance is employed, the slot pressure loss will become increasingly excessive. Since the drag-coefficient equivalent of the suction power c_{d_s} is proportional to the product of $\Delta H/q$ and $\Delta Q/Q_{bl}$ for given values of R and R_δ, c_{d_s} will vary in a somewhat nonlinear fashion with an increasing slot spacing even within the range in which $\Delta H/q$ and $\Delta Q/Q_{bl}$ vary linearly with slot spacing. The savings in c_{d_s} that can be obtained by making the slot spacing smaller than the distance through which $\Delta H/q$ and $\Delta Q/Q_{bl}$ vary linearly with distance are, however, relatively small.

In order to give some indication of the validity of the analysis presented, the drag-coefficient equivalent of the suction power c_{d_s} required to maintain an R_δ of 3420 at various distances behind a slot on the 5-foot-chord NACA 27-215 airfoil has been calculated by using equation (27) and figure 16. The results of the computations are compared with the experimental data obtained for these same conditions in figure 14(b). The Reynolds number based on the wing chord was 8.1×10^6 and the values of $\Delta Q/Q_{bl}$ employed were those determined experimentally which are also shown in figure 14(a). The agreement between the calculated and experimental results for the variation of c_{d_s} with slot spacing is seen to be remarkably good. Had the values of $\Delta Q/Q_{bl}$, calculated according to equation (7), been employed, the agreement would not have been as good. It should be remembered, however, that equation (7) was derived on the assumption of a zero pressure gradient. If the pressure gradients on the airfoil are appreciable or if greater accuracy than that afforded by equation (7) is desired, this equation for calculating the values of $\Delta Q/Q_{bl}$ should not be employed, but rather the data of figure 12, together with some method for calculating the boundary-layer growth which considers the effect of pressure gradient, should be used. Such methods are given in references 7 and 10.

CONCLUDING REMARKS

The results of the experimental investigation presented in this paper show that, by the use of boundary-layer suction through properly designed slots, substantial increases in the extent of laminar flow can be realized with a small expenditure of power at free-stream Reynolds numbers as high as about 7.0×10^6. For example, on an airfoil having an extensive region of unfavorable pressure gradient, the extent of laminar flow was increased by 52 percent of the chord at a Reynolds number of about 7.0×10^6 with an expenditure of suction power the drag-coefficient equivalent of which for one surface was only 0.00037. Somewhat smaller increases in the extent of laminar flow were obtained for a model characterized by extensive favorable pressure gradients. The results also show, however, that much more research is necessary before this type of boundary-layer control can be adequately evaluated. In no case could appreciable increases in the extent of laminar flow be obtained in the present tests at Reynolds numbers higher than 7.0×10^6. The difficulties apparently arose as a result of disturbances introduced into the boundary layer by, perhaps, surface imperfections, free-stream turbulence, or perhaps by the effects of the slots themselves. The source of these disturbances and possible means for avoiding them need further investigation. It might be said that, unless the method of boundary-layer control through slots is ultimately found to decrease the sensitivity of the laminar layer to the usual types of disturbances found on airplane wings, the practical value of the method seems very questionable. In the present tests, the boundary-layer control was not found to decrease noticeably the sensitivity of the laminar layer to surface roughness.

The suction-power analysis developed in the paper with the aid of the results of the experimental investigation of the effects of slot geometry and spacing permits a rational approach to the design of a slot arrangement for an arbitrary airfoil operating under any given conditions such that the suction power may be kept to a minimum. This analysis may prove of value in future investigations and applications of boundary-layer control through slots.

Langley Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Air Force Base, Va., July 8, 1949

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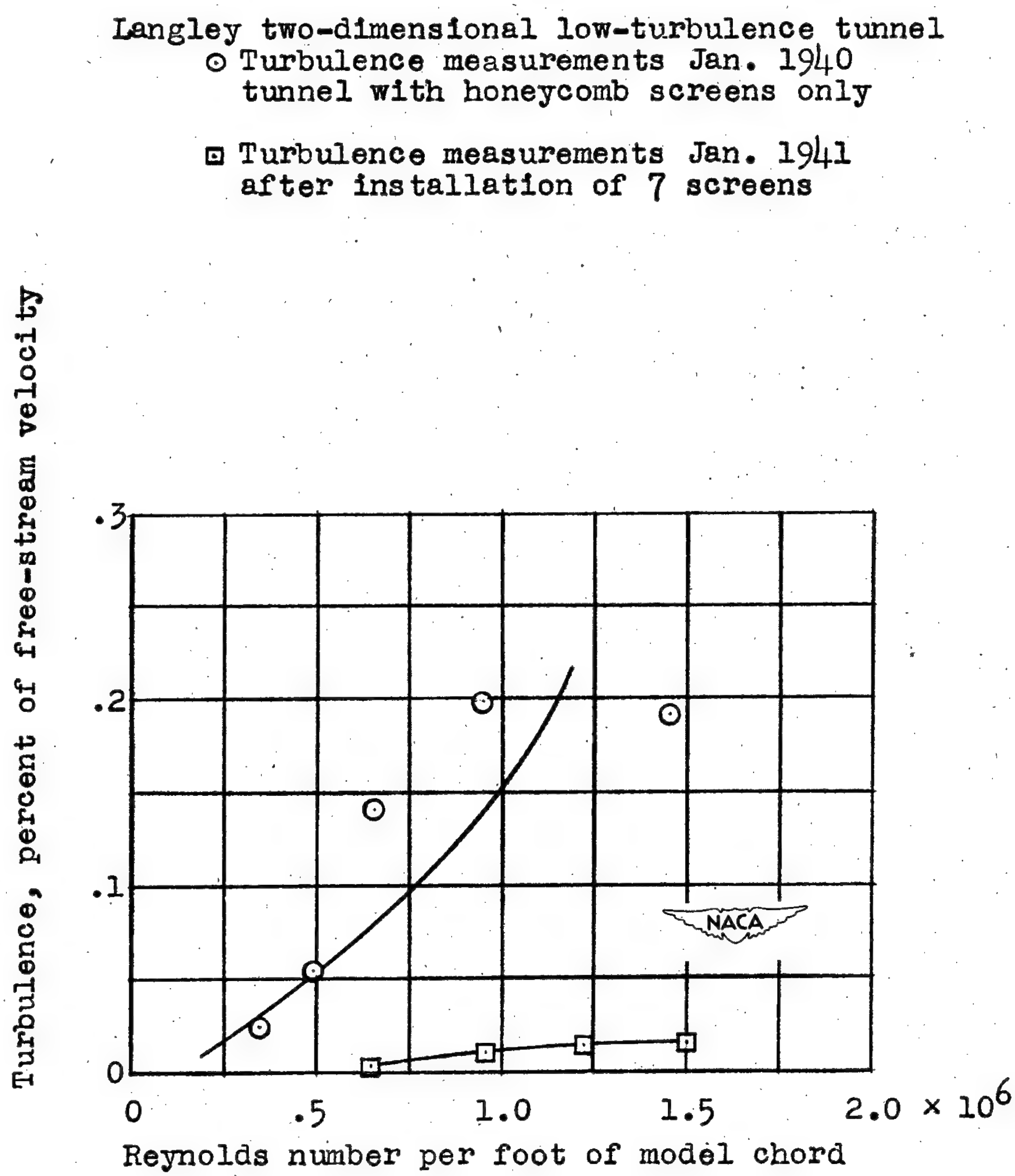


Figure 1.– Turbulence levels of the Langley two-dimensional low-turbulence tunnel (from reference 6).

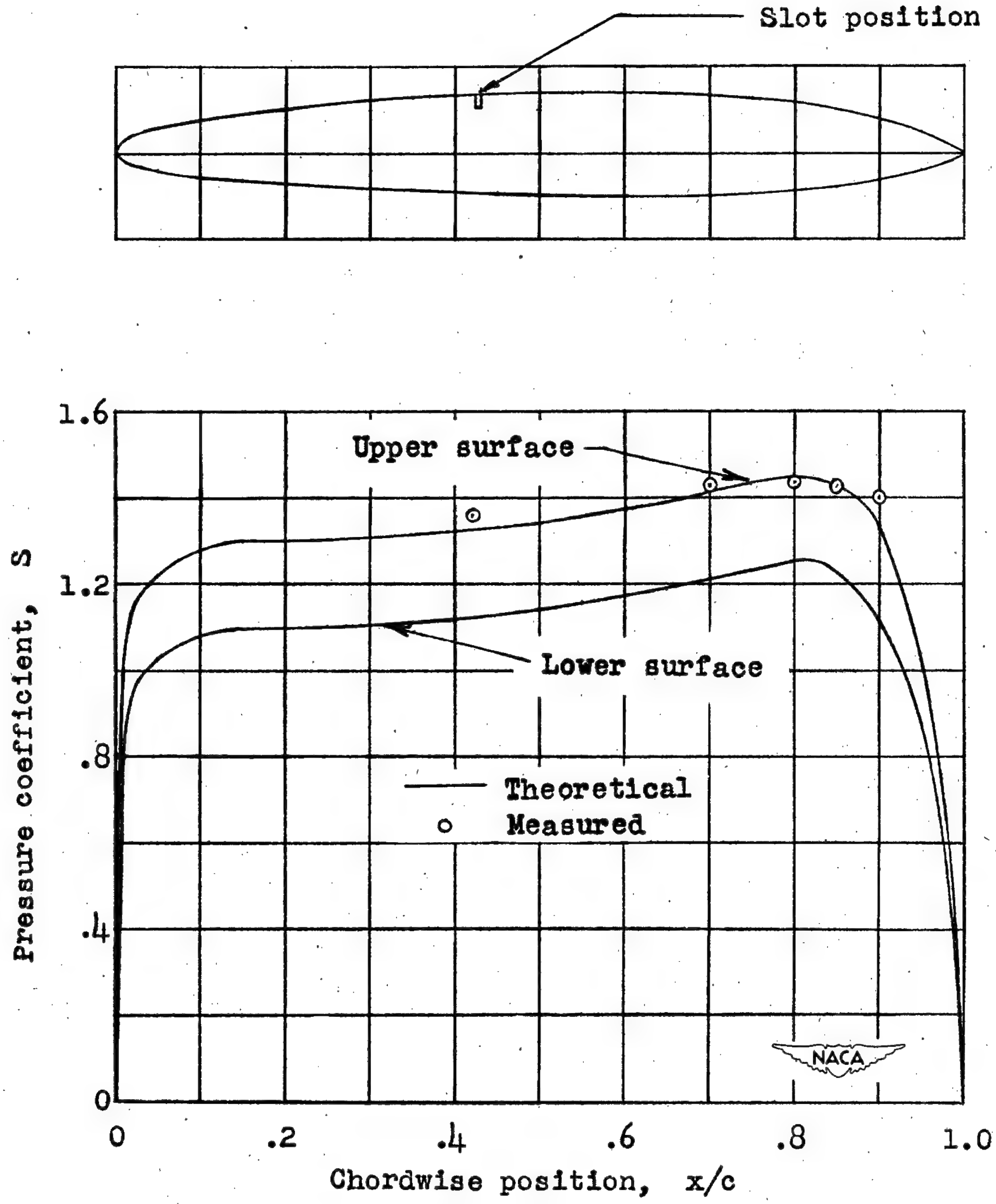
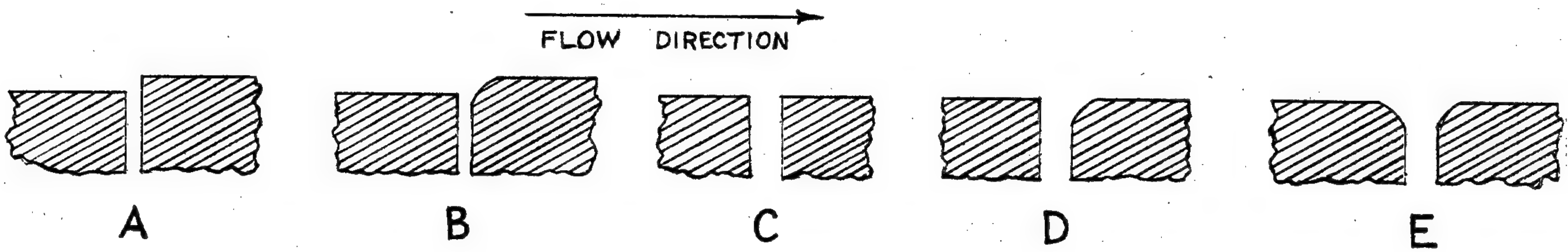
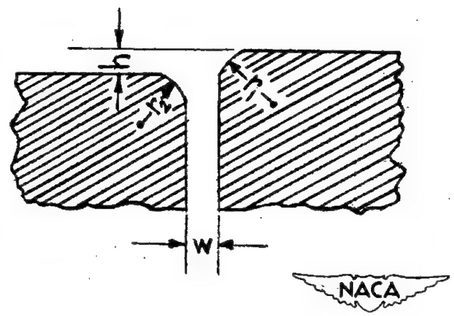


Figure 2.– Pressure distribution and profile shape of NACA 18-212 airfoil section.



(a) Types of normal slots.

TYPE	w	h	r_1	r_2
A	1/64	1/64	—	—
B_1	1/64	1/64	1/64	—
B_2	1/64	1/64	1/32	—
C	1/32	—	—	—
D_1	1/32	—	1/32	—
D_2	1/16	—	1/32	—
D_3	1/16	—	1/16	—
E	1/32	—	1/32	1/32



(b) Dimensions of normal slots in inches.

Figure 3.– Types and dimensions of normal slots investigated.

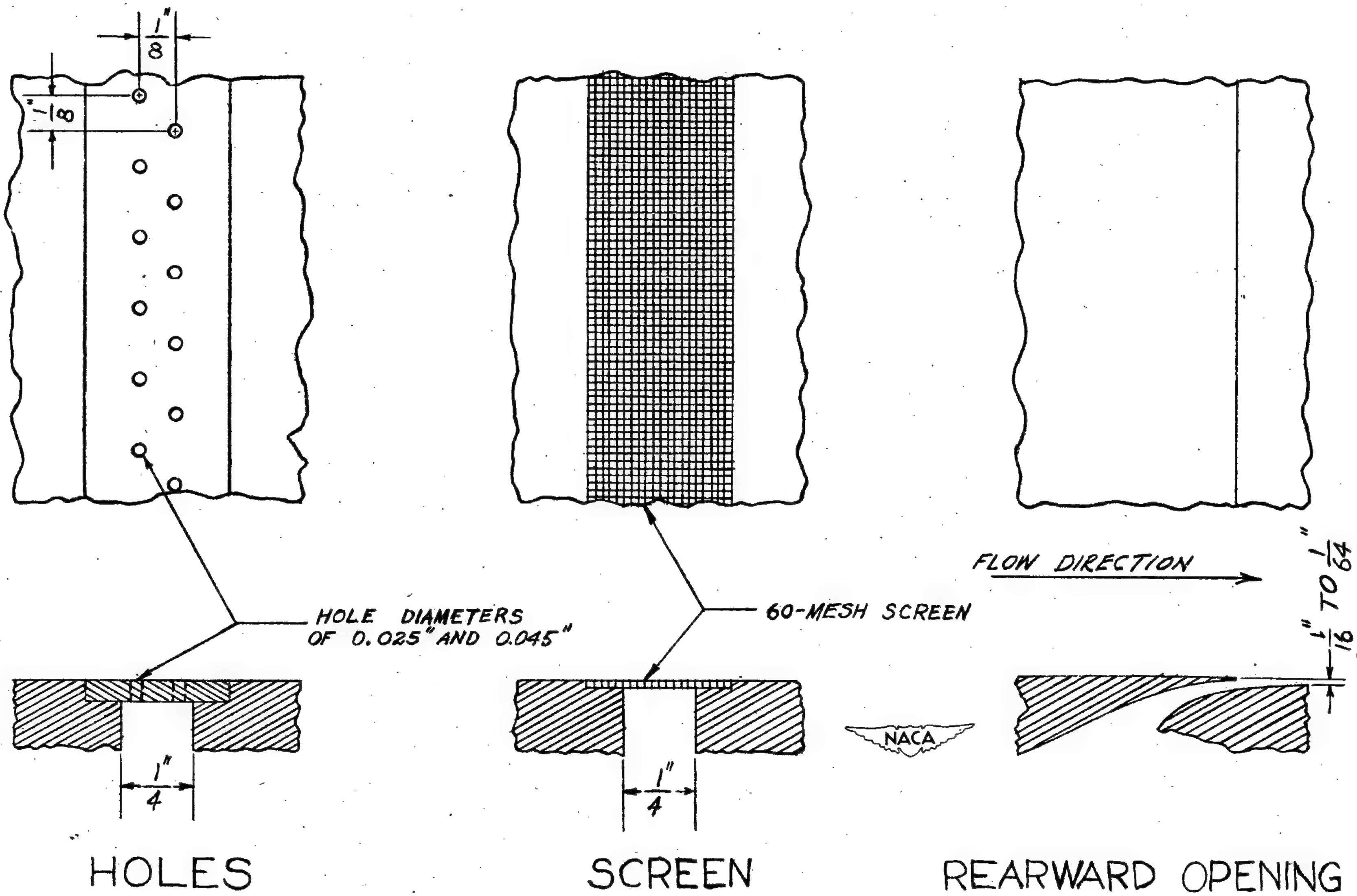
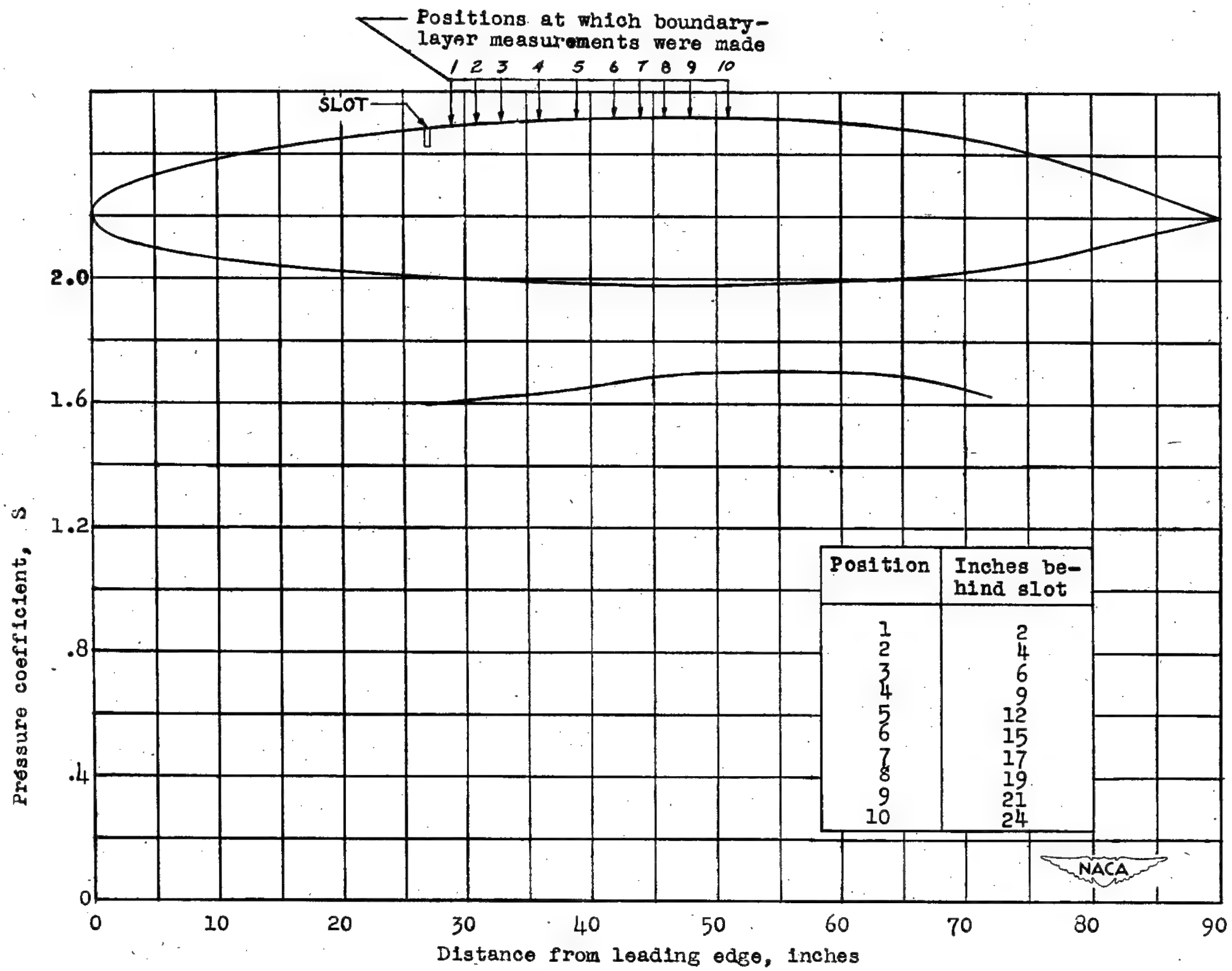


Figure 4.– Different types of slots investigated.



Position	Inches behind slot
1	2
2	4
3	6
4	9
5	12
6	15
7	17
8	19
9	21
10	24

Figure 5.— Experimental pressure distribution over a portion of the upper surface and profile shape of NACA 27-215 airfoil section together with slot location and positions at which boundary-layer measurements were made.

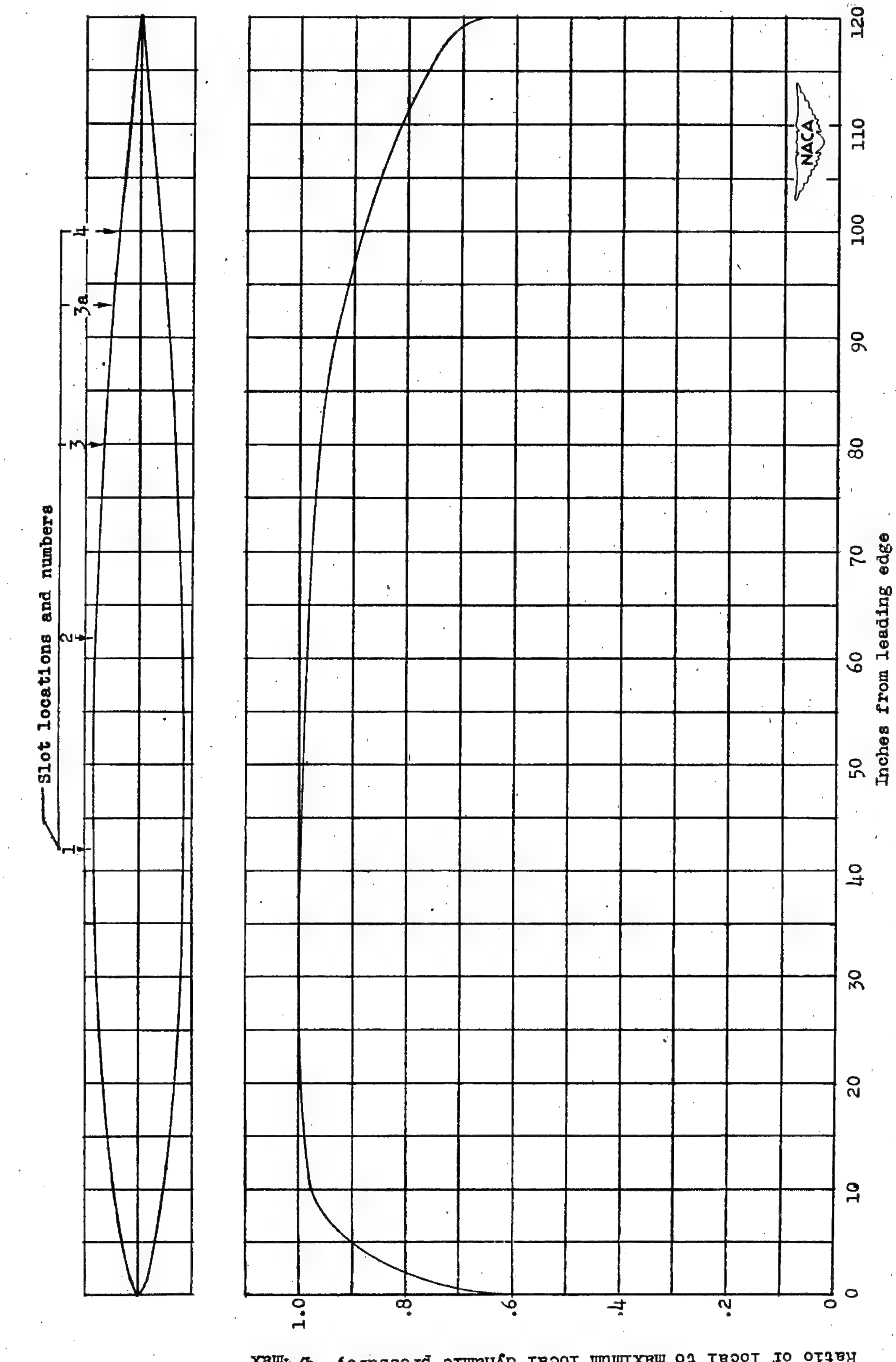


Figure 6.- Experimental pressure distribution and profile shape of NACA 0007-34 airfoil section together with slot locations.

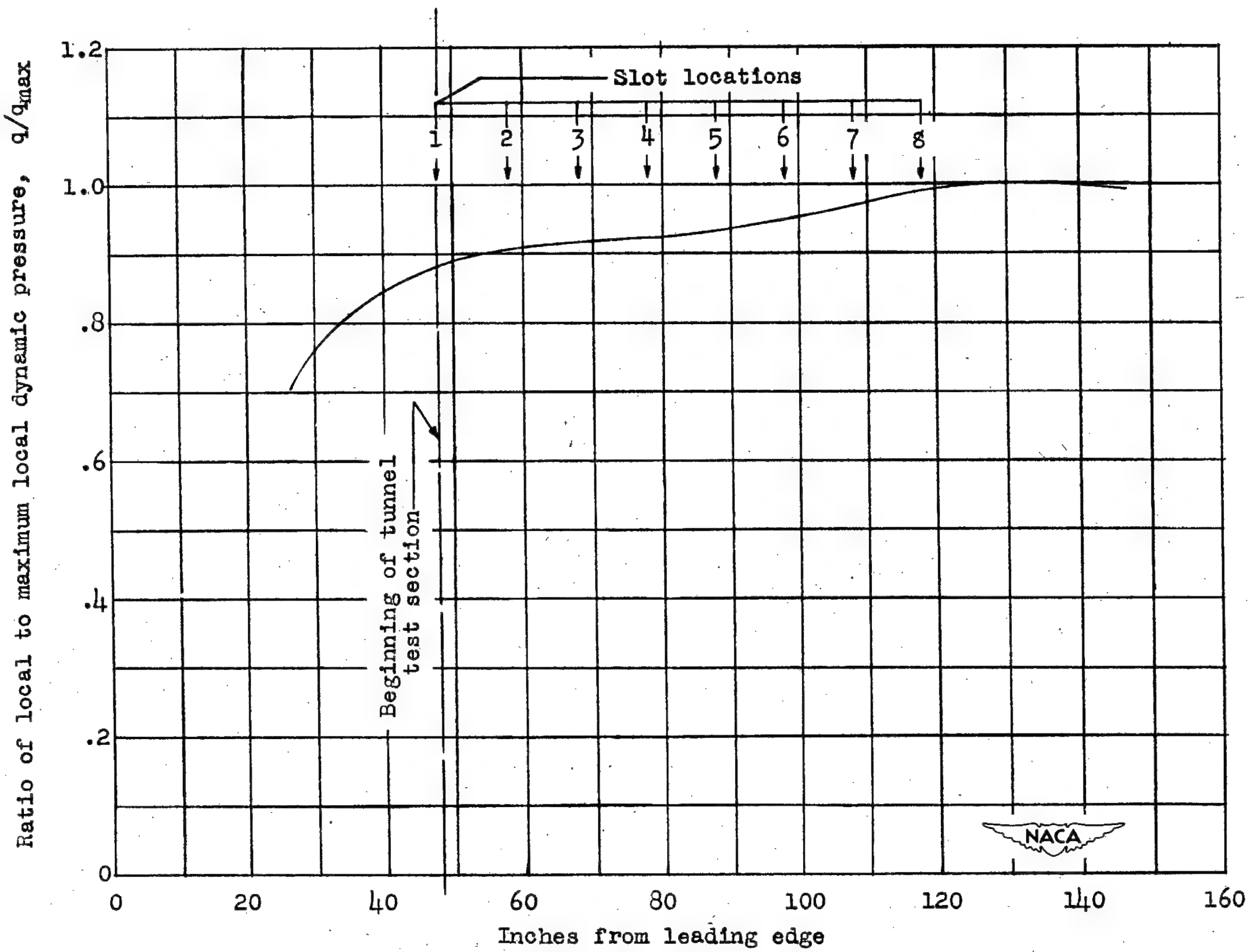


Figure 7.– Test configuration for investigations of effect of suction slots on flow in a favorable pressure gradient.

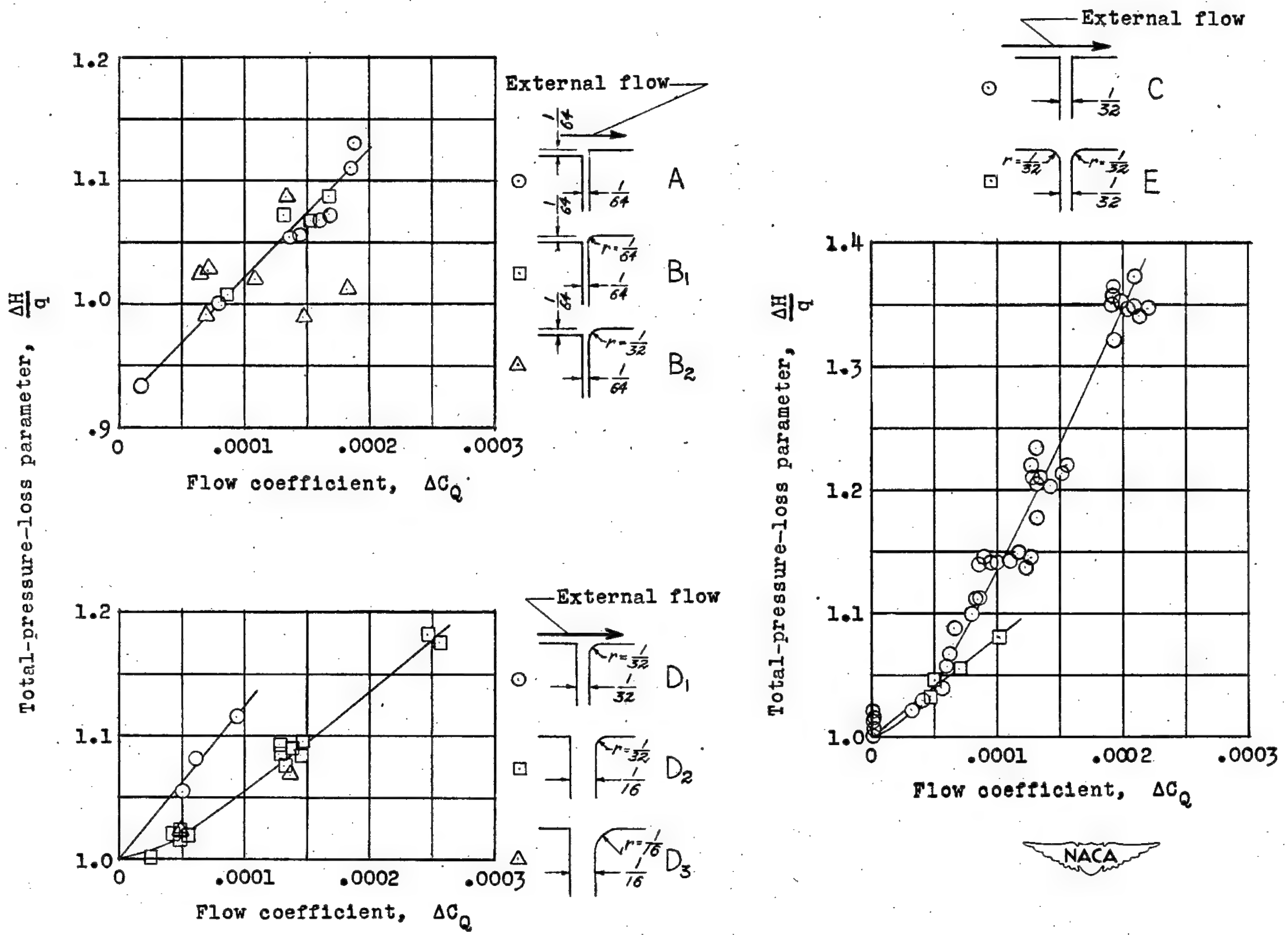


Figure 8.– Variation of total pressure loss with quantity of flow for the different types of normal slot investigated; $R = 4.7 \times 10^6$ to $R = 8.0 \times 10^6$. Slot dimensions are given in inches.

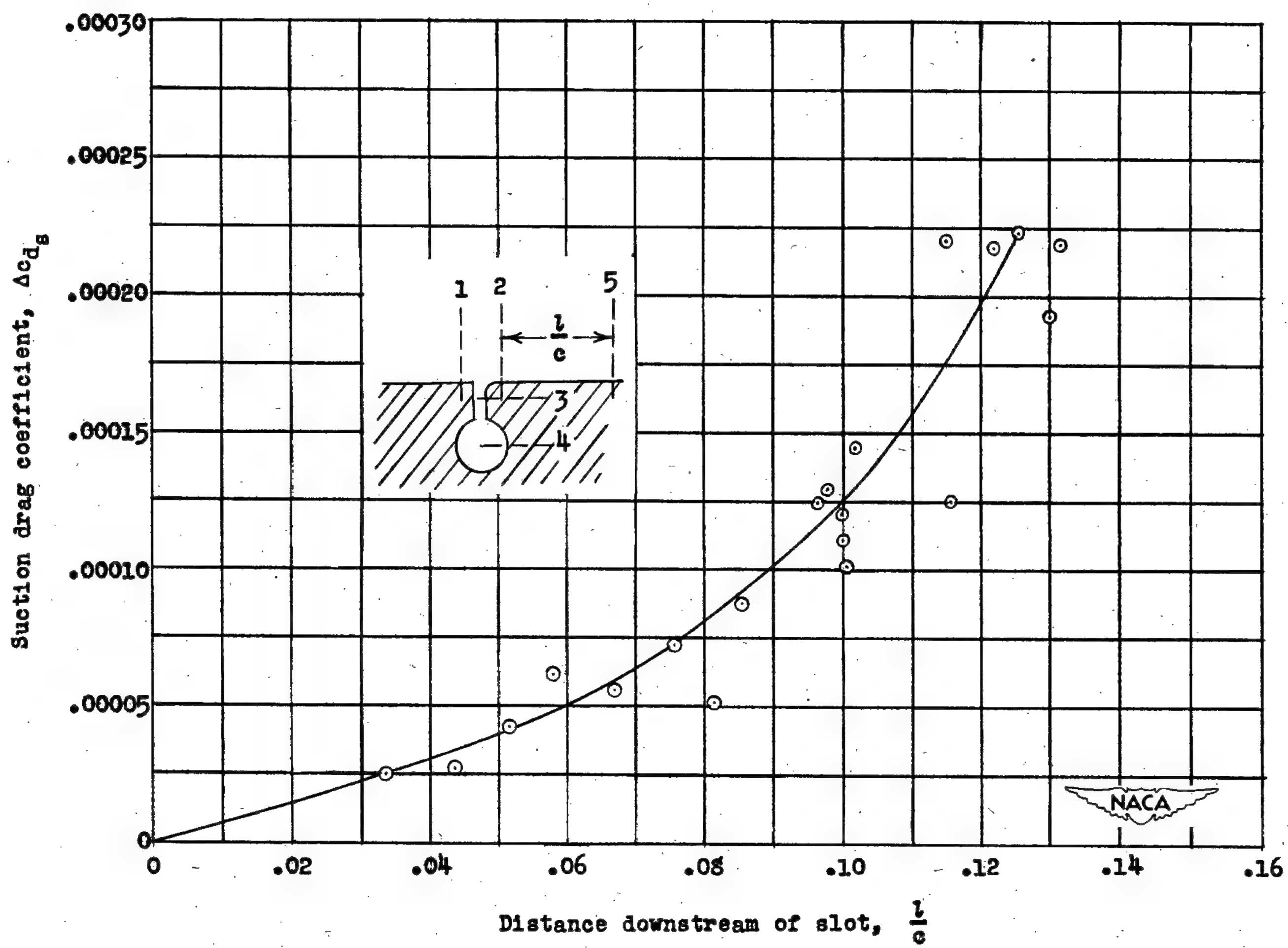
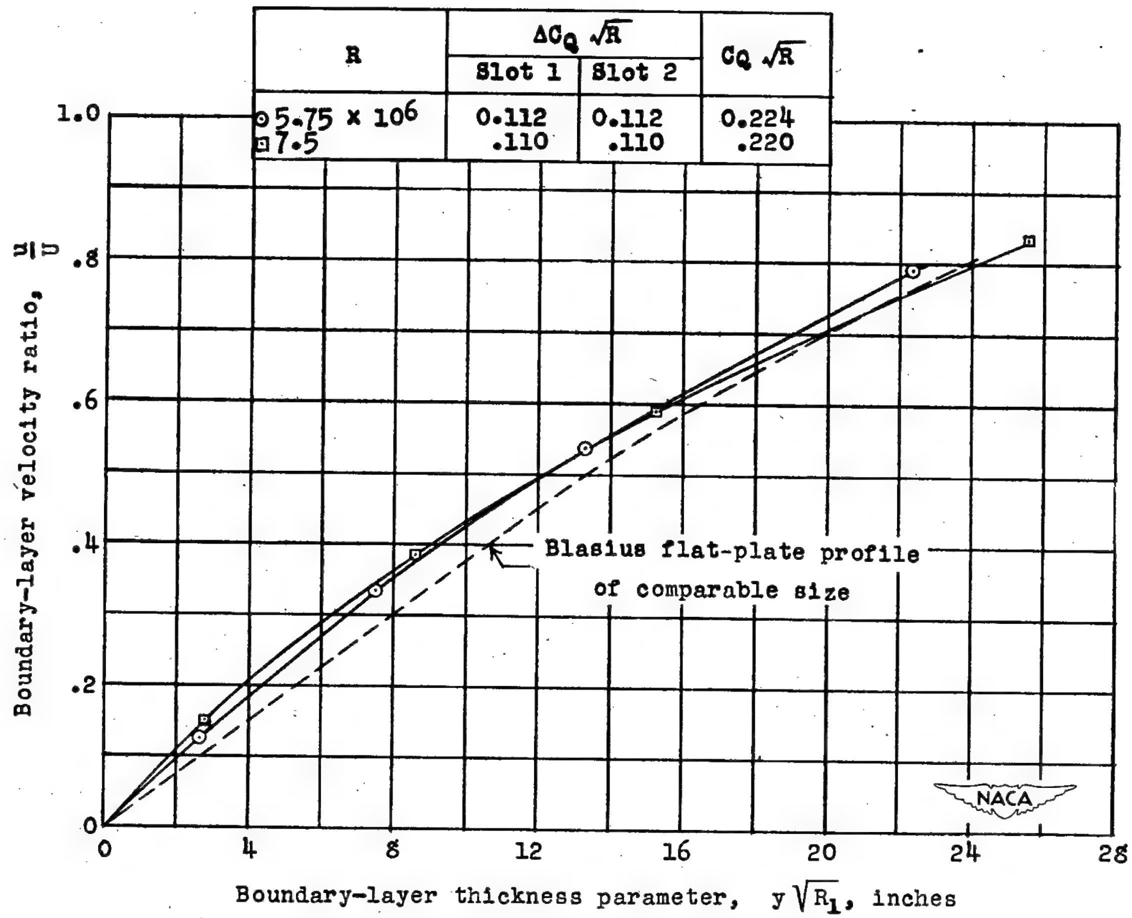


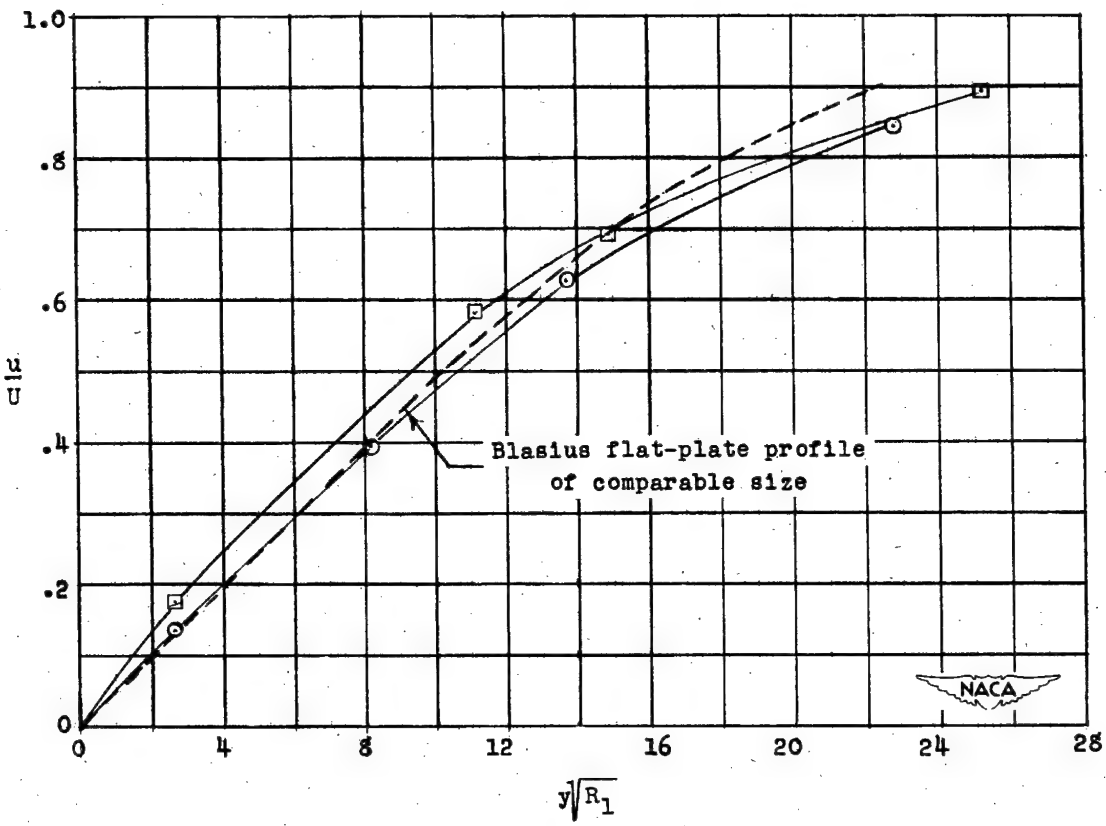
Figure 9.– Experimental variation of suction drag coefficient with the distance downstream of slot where R_{δ_5} becomes equal to R_{δ_1} for the NACA 27-215 airfoil section with a suction slot at approximately the midchord position. $R_{\delta_1} = 3420$; $R = 8.1 \times 10^6$; $\frac{\delta_1}{w} = 0.93$; $\frac{q_1}{q_o} = 1.75$.



(a) 0.5 inch ahead of slot 3; slots 1 and 2 in operation.

Figure 10.– Boundary-layer profiles measured at various positions on the NACA 0007-34 airfoil. R based on maximum velocity on airfoil.

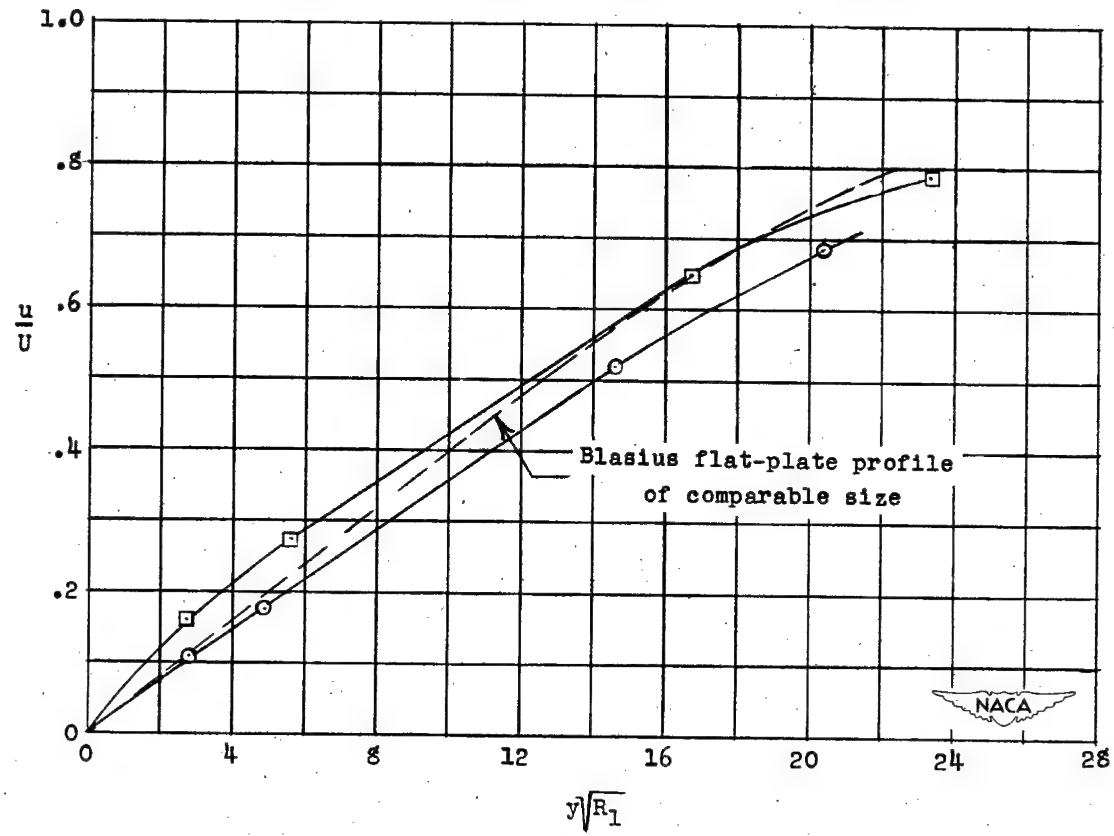
R	$\Delta C_Q\sqrt{R}$			$C_Q\sqrt{R}$
	Slot 1	Slot 2	Slot 3	
⊙ 5.75×10^6	0.140	0.250	0.134	0.524
⊡ 7.5	.122	.223	.159	.504



(b) 10 inches behind slot 3; slots 1, 2, and 3 in operation.

Figure 10.— Continued.

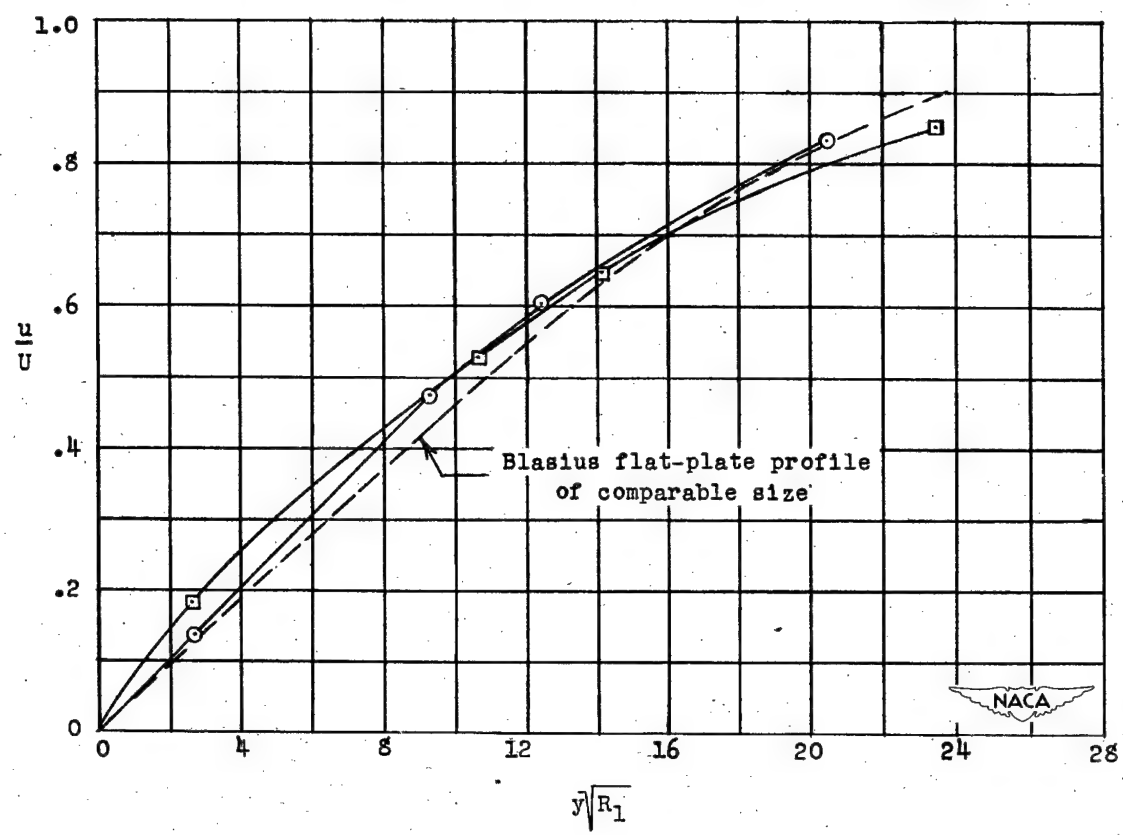
R	$\Delta C_Q\sqrt{R}$			$C_Q\sqrt{R}$
	Slot 1	Slot 2	Slot 3	
⊙ 5.75×10^6	0.123	0.222	0.152	0.497
⊡ 7.5	.143	.257	.090	.490



(c) 15 inches behind slot 3; slots 1, 2, and 3 in operation.

Figure 10.– Continued.

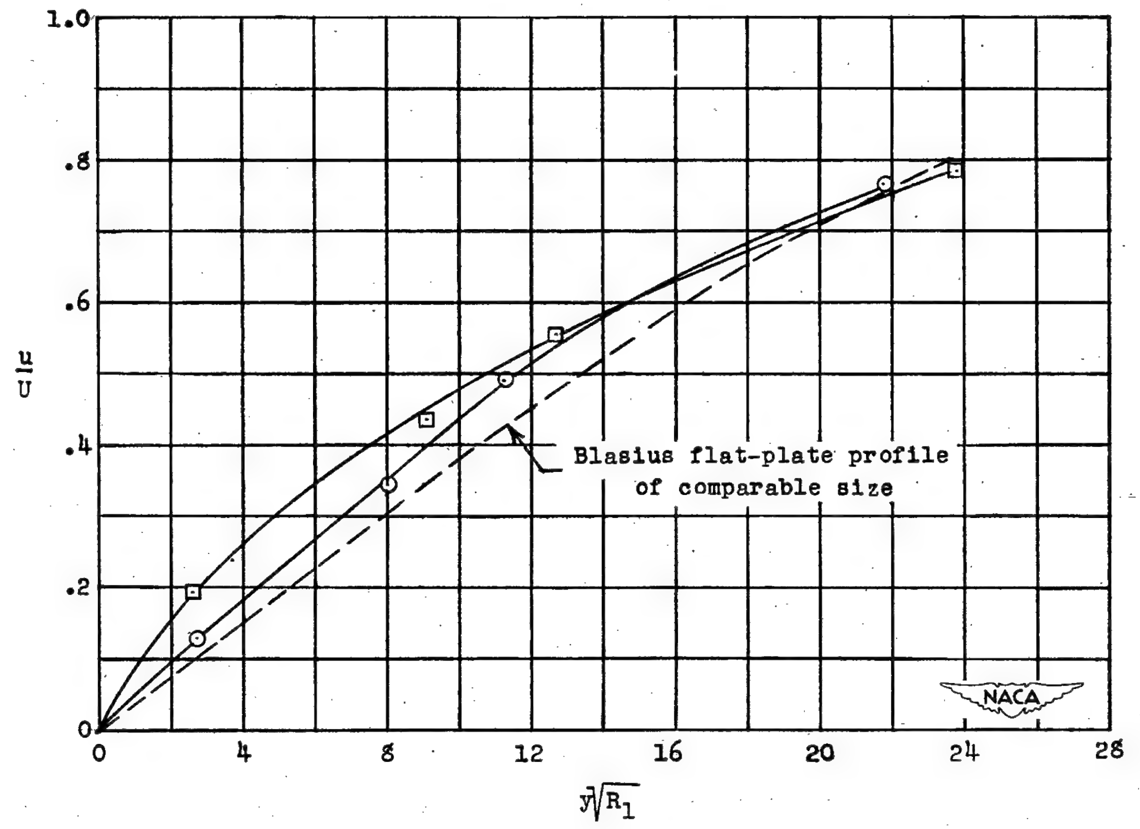
R	$\Delta C_Q\sqrt{R}$				$C_Q\sqrt{R}$
	Slot 1	Slot 2	Slot 3	Slot 3a	
⊙ 5.75×10^6	0.143	0.252	0.136	0.123	0.654
⊡ 7.5	.125	.220	.117	.173	.635



(d) 0.5 inch ahead of slot 4; slots 1, 2, 3, and 3a in operation.

Figure 10.– Continued.

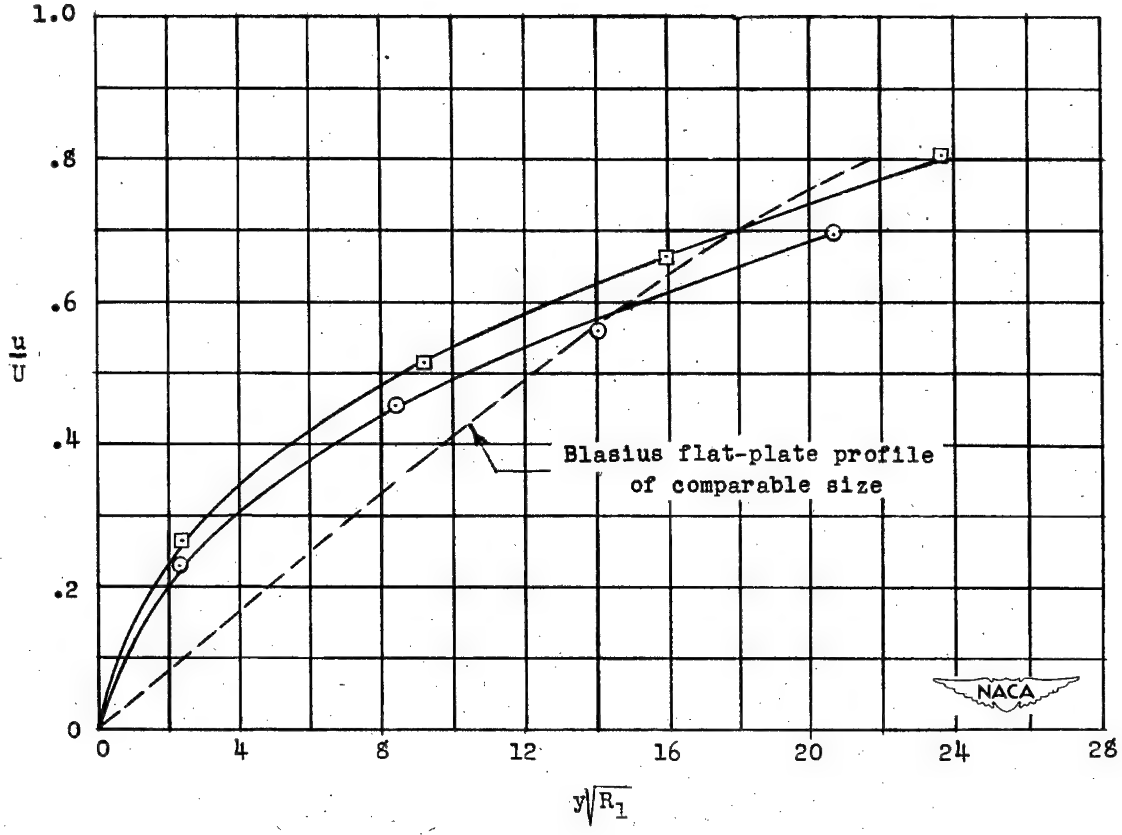
R	$\Delta C_Q\sqrt{R}$					$C_Q\sqrt{R}$
	Slot 1	Slot 2	Slot 3	Slot 3a	Slot 4	
⊙ 5.75×10^6	0.142	0.254	0.133	0.073	0.210	0.812
⊡ 7.5	.121	.214	.115	.064	.207	.721



(e) 10 inches behind slot 4; slots 1, 2, 3, 3a, and 4 in operation.

Figure 10.– Continued.

R	$\Delta C_Q\sqrt{R}$					$C_Q\sqrt{R}$
	Slot 1	Slot 2	Slot 3	Slot 3a	Slot 4	
○ 5.75×10^6	0.139	0.263	0.132	0.088	0.296	0.918
⊡ 7.5	.127	.229	.111	.109	.365	.941



(f) 15 inches behind slot 4; slots 1, 2, 3, 3a, and 4 in operation.

Figure 10.– Concluded.

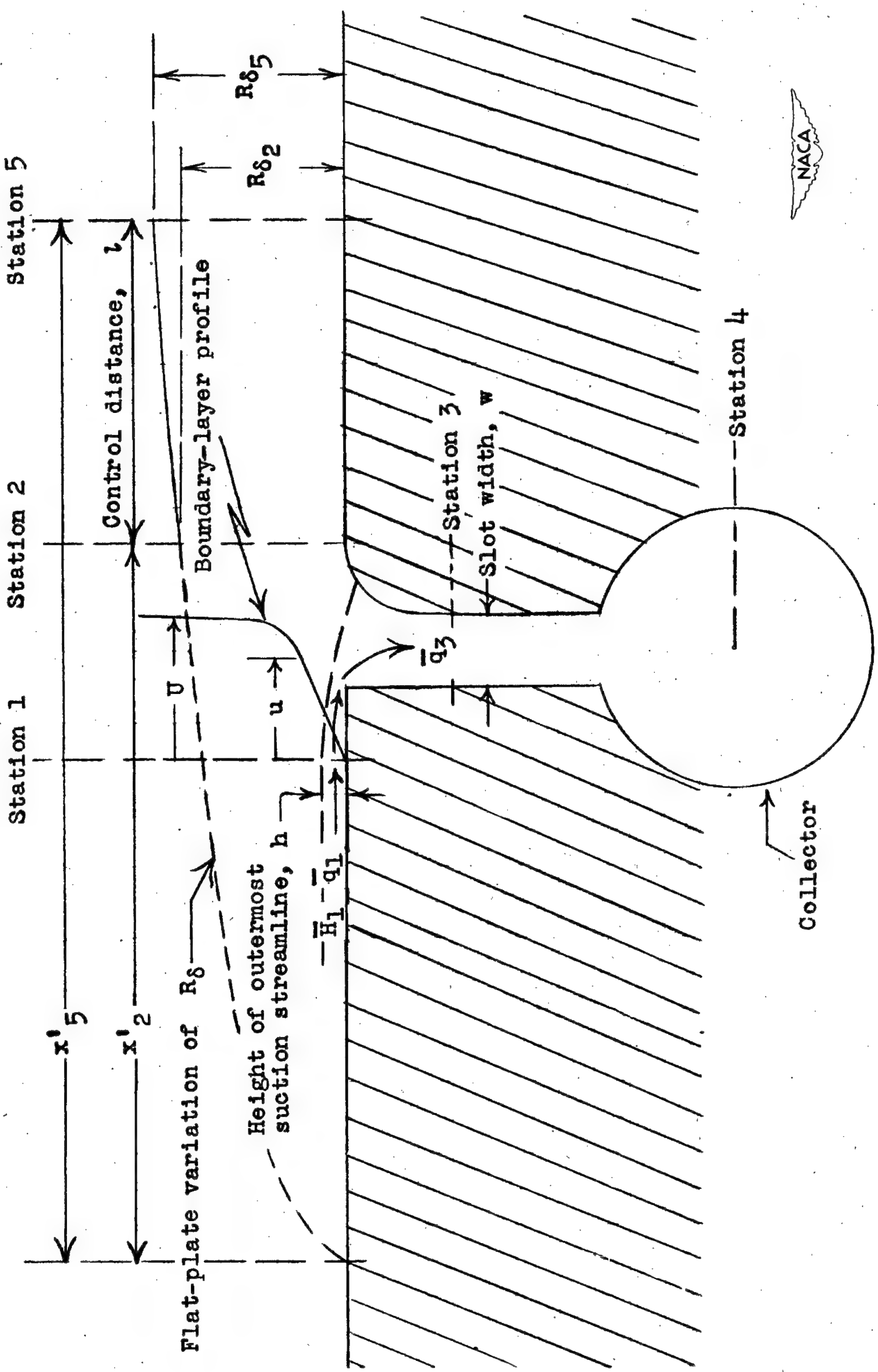


Figure 11.- Diagram of slot geometry and air-flow pattern for slot pressure-loss analysis.

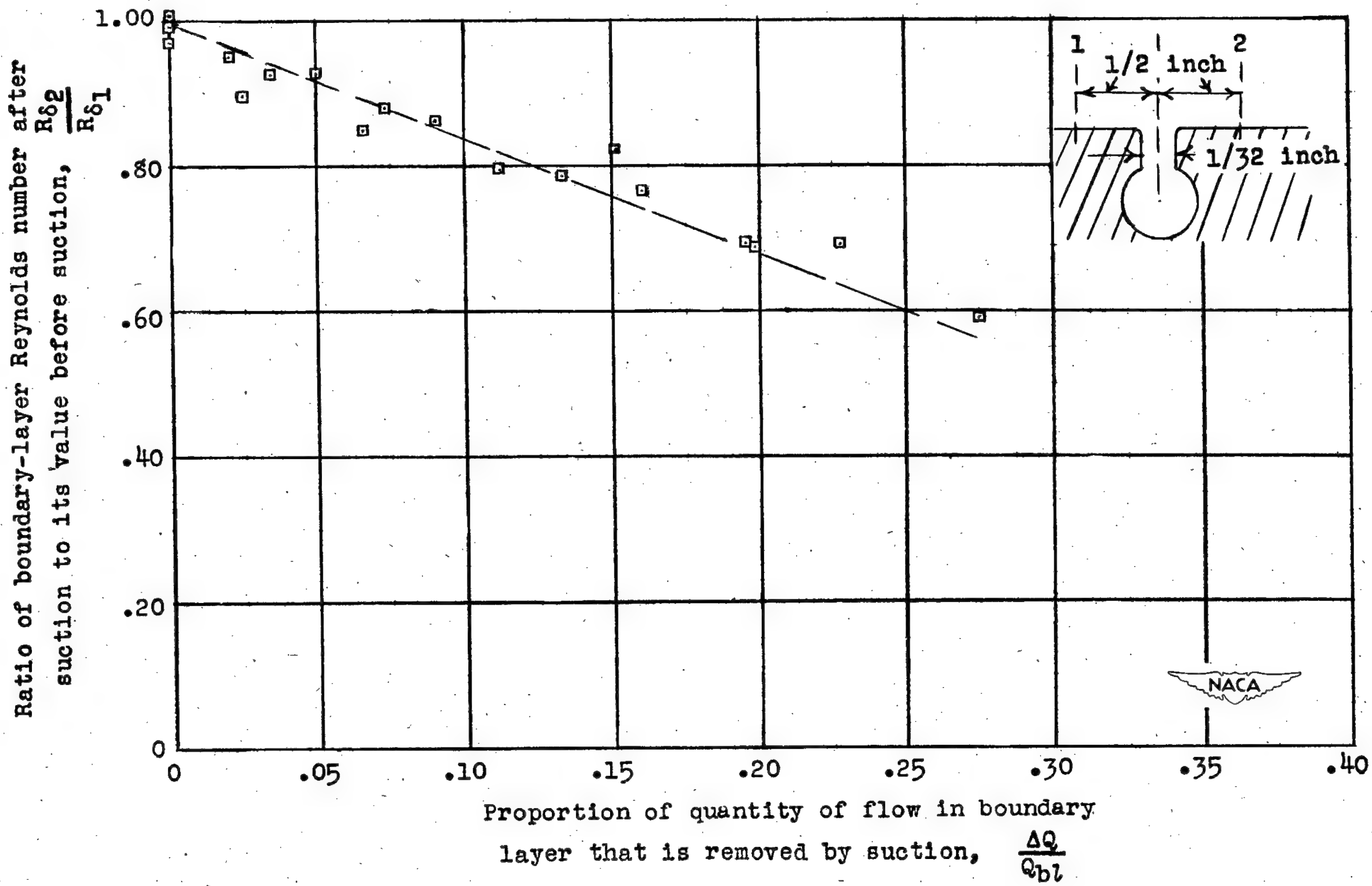


Figure 12.- Variation of boundary-layer Reynolds number across slot with suction quantity ratio. R_{δ_2} was based on a Blasius profile having the same loss in momentum as the profile measured rearward of slot.

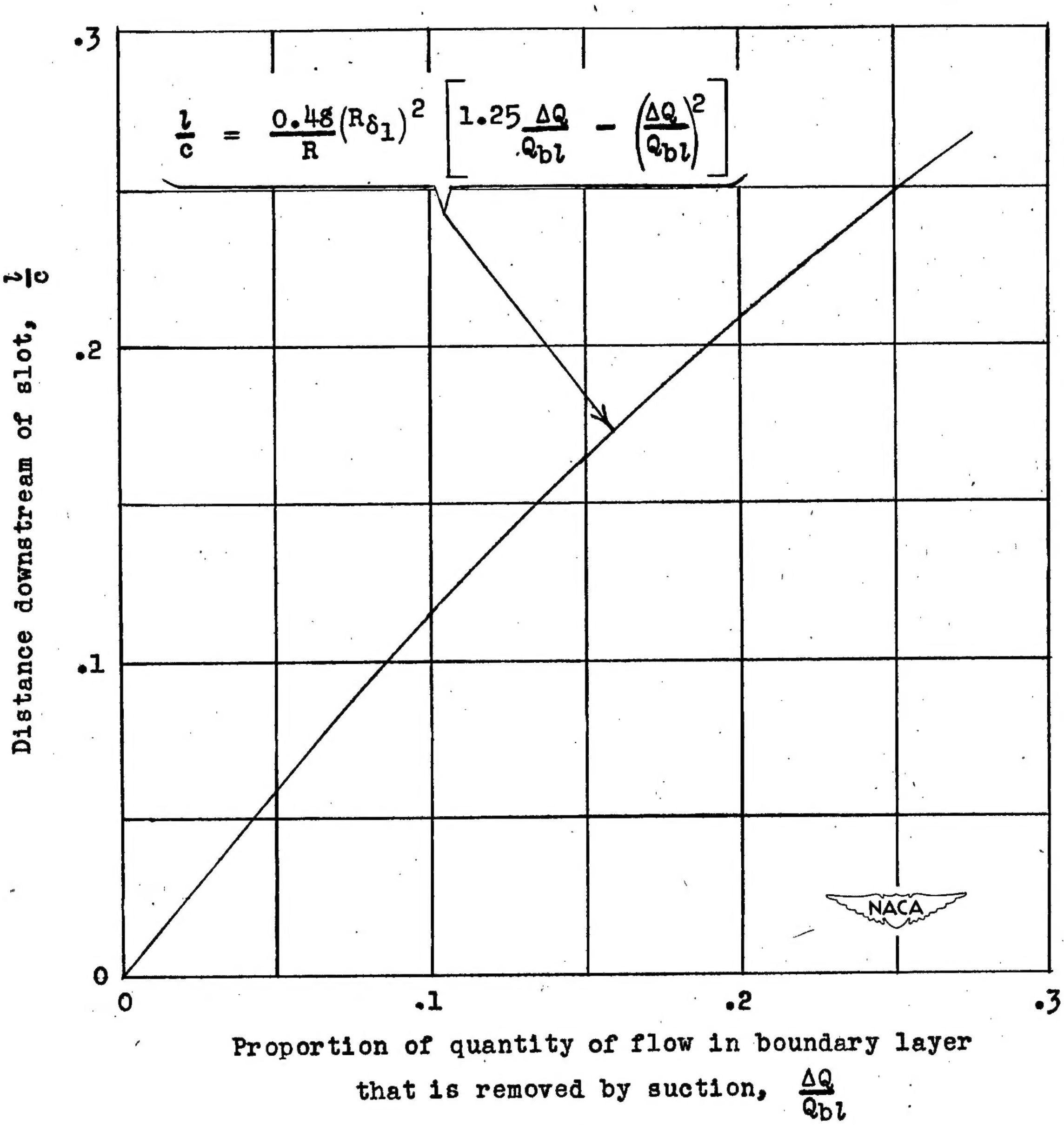
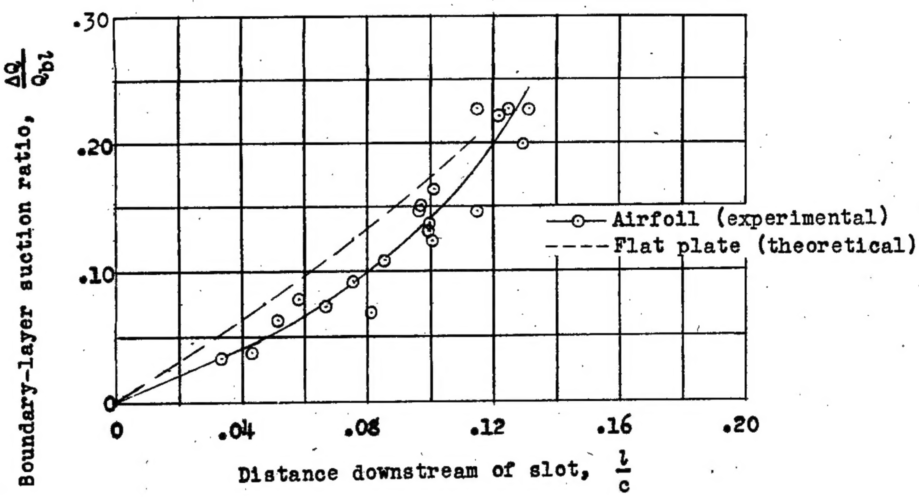
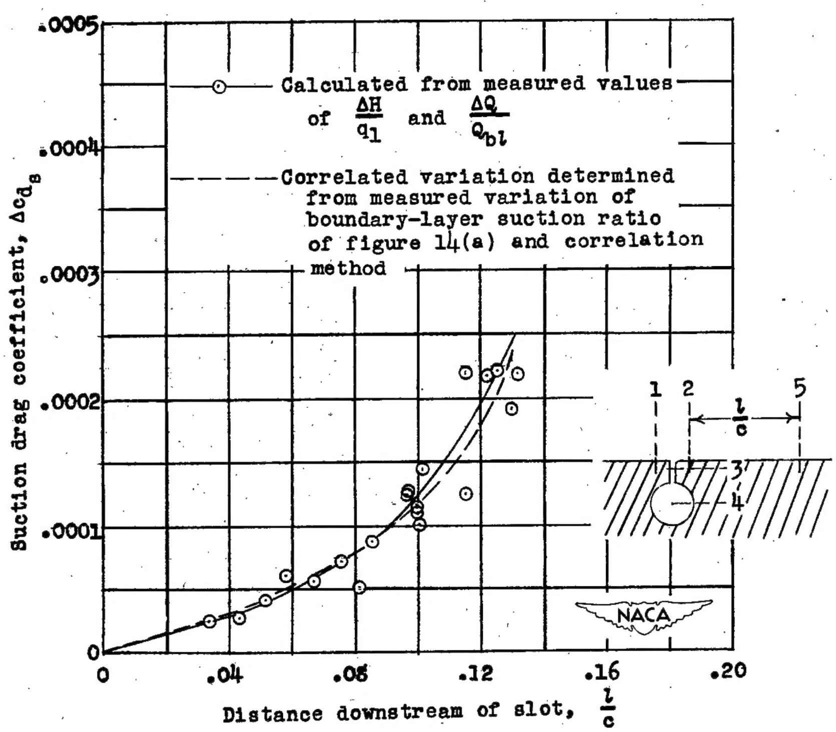


Figure 13.– Sample flat-plate variation of suction flow required for different slot spacings; $\frac{0.48(R_{\delta_1})^2}{R} = 1$.



(a) Variation of boundary-layer suction ratio with slot spacing.



(b) Experimental and correlated variations of suction drag coefficient with distance downstream of slot.

Figure 14.– Variations in suction drag and suction flow with the distance downstream of slot where R_{δ_5} becomes equal to R_{δ_1}; $R_{\delta_1} = 3420$; $R = 8.1 \times 10^6$; $\frac{\delta_1}{w} = 0.93$; $\frac{q_1}{q_o} = 1.75$.

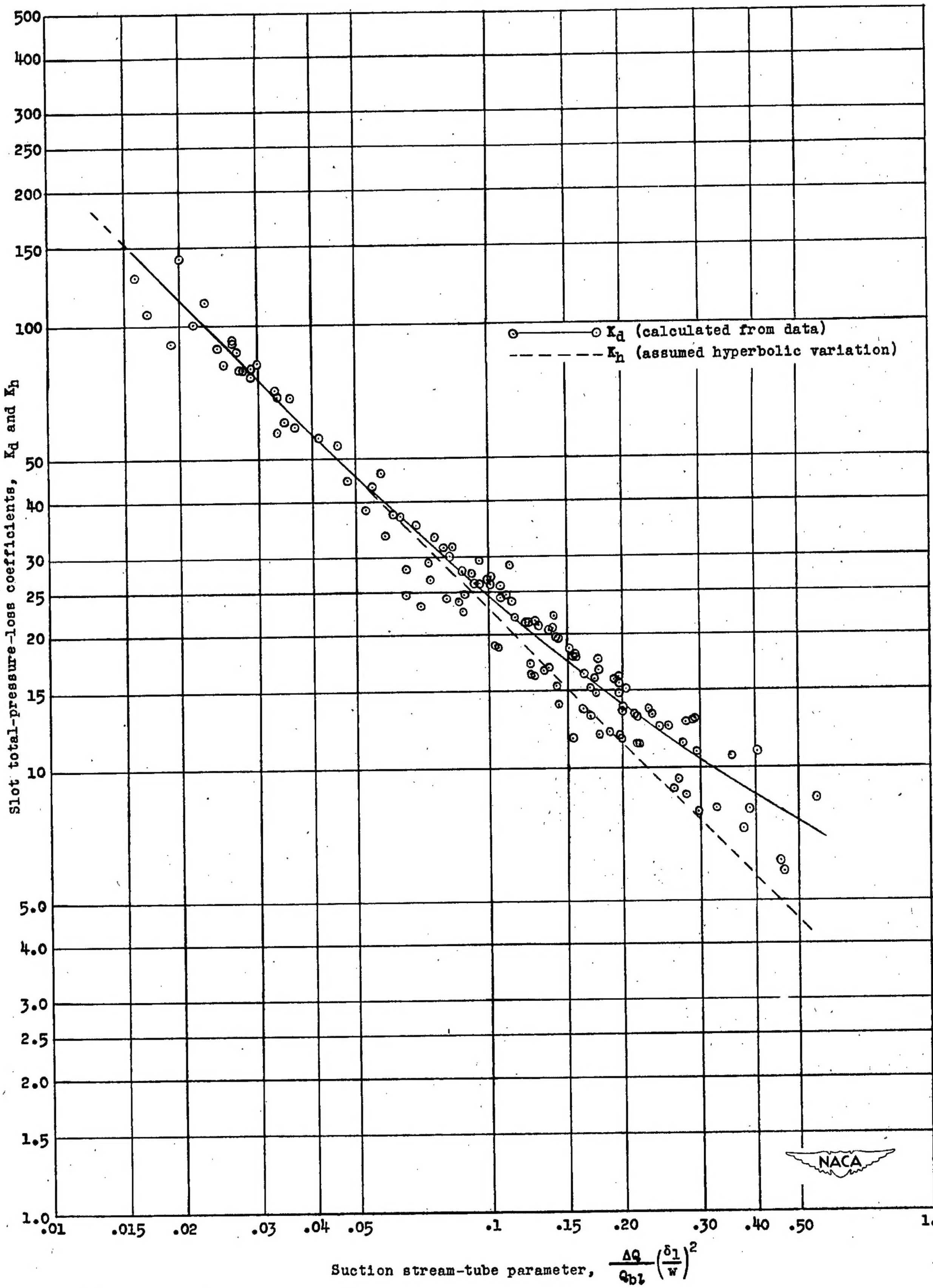


Figure 15.- Experimental and hyperbolic variations in the slot total-pressure-loss coefficient with the suction stream-tube parameter.

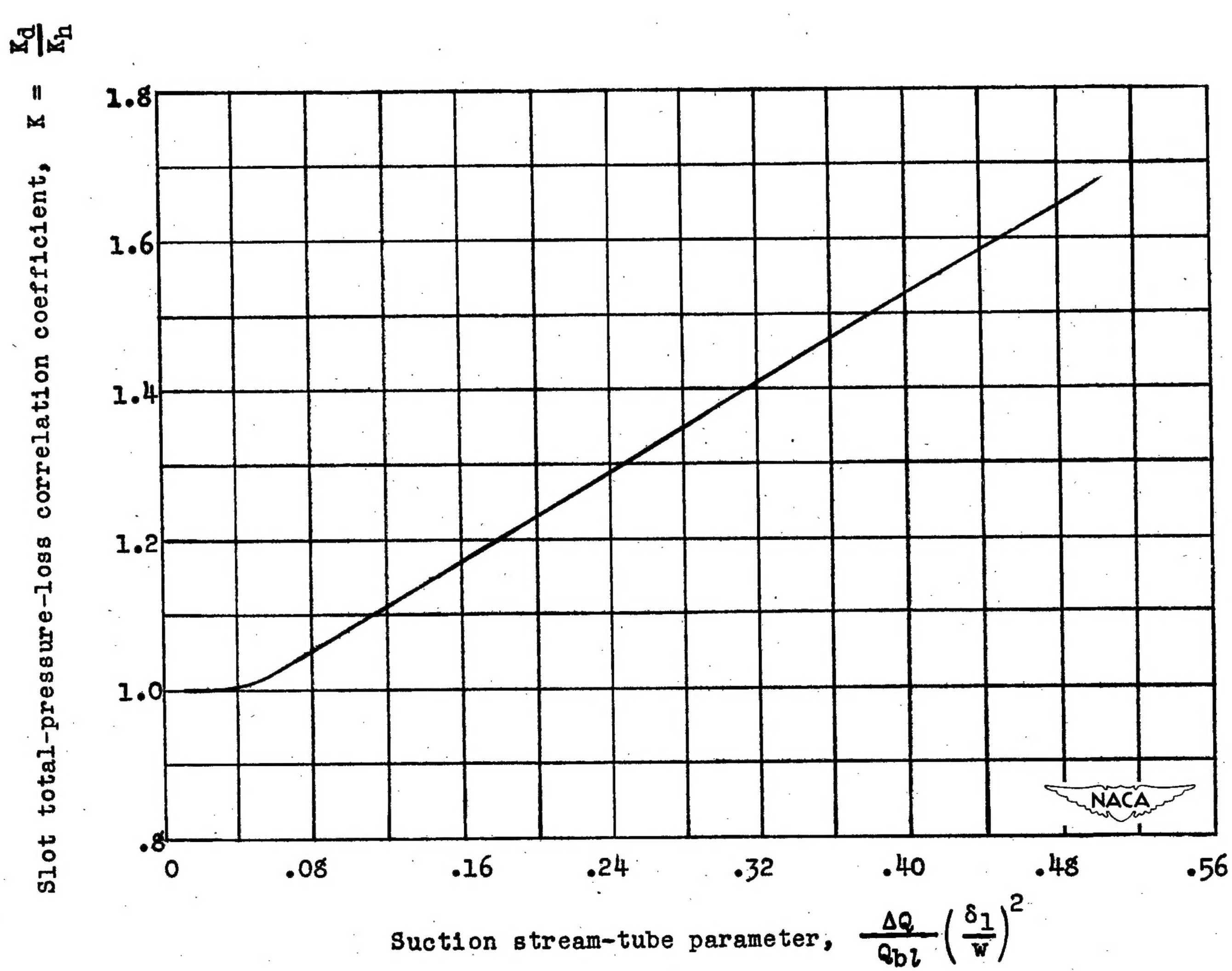


Figure 16.- Variation of the ratio of the experimental slot total-pressure-loss coefficient K_d to the theoretical relationship K_h with the suction stream-tube parameter.